COPPER AND LEAD MINERALIZATION

in the Bageshwar Area, District Almora (U. P.)

BY

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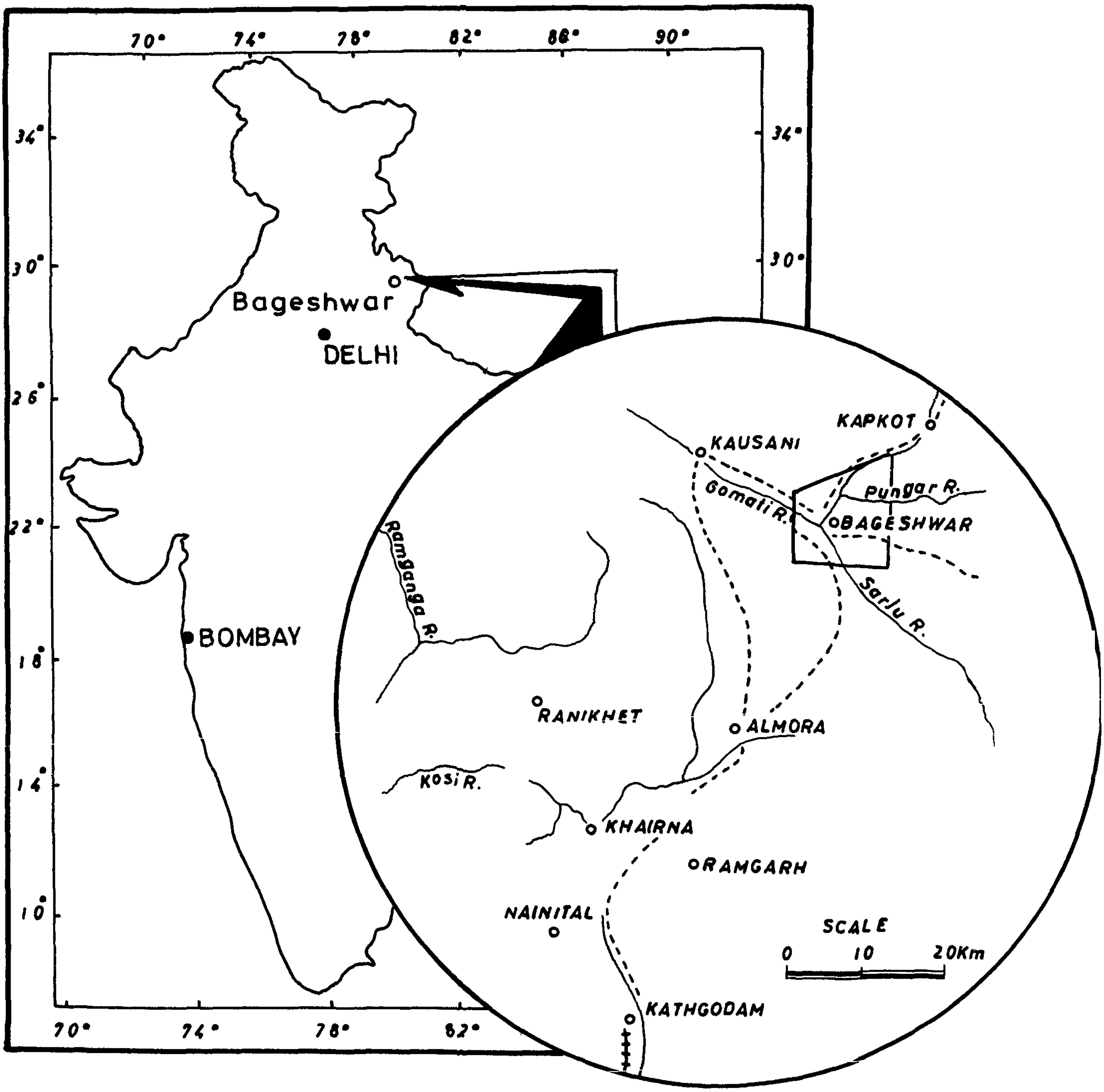

FIG. 1. MAP SHOWING THE LOCATION OF THE AREA UNDER INVESTIGATION.

Chapter - I

INTRODUCTION AND PREVIOUS INVESTIGATIONS

INTRODUCTION

Location, Extent and Communication

Bageshwar (29°50'18", 79°46'24") is a flourishing town in the hilly Almora district of Uttar Pradesh, India. It is located near the confluence of the Sarju and Gomati rivers at a distance of about 56 miles NNE of the Almora district headquarters and about 110 miles NNE of Kathgodam, a terminal station in the North-Eastern Railways. The town occupies a place in the remote interior of the Kumaon division on the old pilgrim road between Almora and Badrinath (30°44' N, 79°32' E). The motorable roads on the south, north and east of Bageshwar were constructed only after 1962. The town is also connected to Kathgodam (see Fig. 1) via Almora and Garur (29°53'56", 79°37'04") by another good motorable road and a mule track. The area selected for geological surveying and study is about 55 square miles around Bageshwar between 79°42'E longitude to 79°48'E longitude and 29°46'52" N latitude to 29°54'24"N latitude. It is included in the one inch to a mile topographical sheet Nos. 53, 0/9 and 0/13 published by the Survey of India (Fig. 2). The central part of the area is occupied by the Sarju river valley (Fig. 2) which is surrounded by some of the lofty ridges of the Inner Himalayan zone.

Purpose of the work

Although the occurrences and ancient mining of copper and lead around Bageshwar were known for the last 100 years, very few authoritative published work on the mode of occurrence, mineralogy, structure and genesis of the deposits is available. As far as the stratigraphy and structure of the area is concerned, a little more is known. Among the recent workers, who have given some informations regarding the geology of the ore-deposits, their mode of occurrence and physical nature, mention may be made of Subramanyam and Jain (1960a, 1960b, 1961), Jhingran and Mathur (see Roy 1961), Nautiyal (1962), and Swarup and Misra (1945). Gansser (1964, Plate 1A) has only given the broad structural pattern of the area in his geological map of the Himalayas. With such a background of previous work, the present investigation was planned in such a way as to bring out not only the structure and stratigraphy of the area in some detail, but also the nature of wall rock alteration due to sulphide mineralization, in addition to the mineralogy and paragenesis of the copper and lead ores and finally, their genesis.

The investigation was undertaken at the suggestion of Dr. S.H.Rasul who also supervised the entire work. It was obviously of considerable scientific interest and thought-provoking. In course of the present work, the author came across several exciting problems in the field as well as in the laboratory. It has also opened some new avenues of thinking. For most of the observations, discussions, judgments and conclusions the author is responsible.

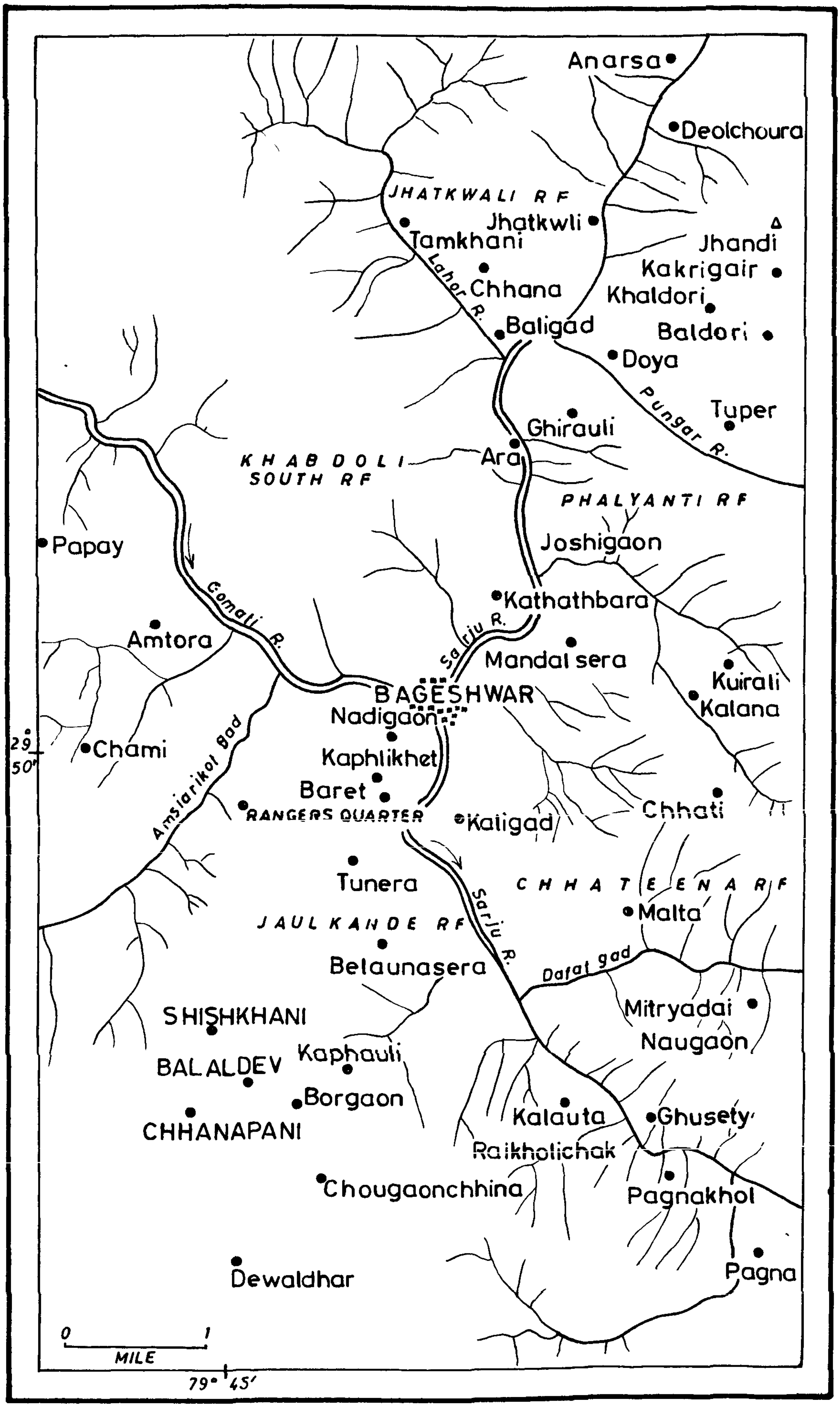

FIG. 2 MAP SHOWING THE TOPOGRAPHY AND ENVIRONS OF BAGESHWAR

Methods and presentation of the work

Broadly, the work was carried out according to the following programme:

1. Field investigations - a) Preparation of a geological map and structural sections of the area showing the more important structural features of the country rocks, including the host rocks of copper and lead deposits; b) sampling of the relevant rocks, minerals and ores for petrographic and ore microscopic work; c) restricted sampling of the mineralized rocks for chemical analysis and d) collection of data for geomorphological studies.

2. Laboratory Study - a) Preparation of thin and polished sections of rocks and ores and their study in transmitted and reflected light respectively; b) determination of micro hardness of the ore minerals using a micro-hardness tester.

3. Chemical analyses of rocks samples:

The work is presented in the following order:

i) Introduction and previous investigations.
ii) Stratigraphy and lithology
iii) Structure and morphotectonics.
iv) Petrography and petrogenesis.
v) Wall rock alteration, ore-zoning and guide to ore deposition.
vi) Mineragraphy and paragenesis of the opaque minerals.
vii) Genesis of the copper and lead deposits.
viii) Summary and conclusions

General topography

The topography of the area is very rugged and the relief of the area is 3,500'. The hills, valleys and ridges are somewhat arcuate. In the southwest of Bageshwar the ridges roughly run in an east-west direction. The ranges to the south of Pungar river (Fig. 2) attain an elevation upto 5,500 ft. and strike NW-SE.

Broad alluvium-covered valleys may well be seen in Nandal Sera-Kathathbara region, Balauna Sera, Nadigaon region etc. The area is drained by the Sarju, Gomati, Pungar, Lahor rivers and their tributaries.

<u>Drainage</u>

There are two main rivers viz., the Sarju and Gomati which are largely responsible for drainage of the area. In general, the drainage system of the area has a trellis pattern. The main tributaries of the Sarju river are in general, along strike of the formations or along faults etc. and may thus be regarded as of subsequent type (see Sparks 1964, p.9). In majority of cases, the tributaries of subsequent streams are of insequent type because they appear neither to depend upon the initial depressions nor upon the weakness in the rocks.

In the north of Bageshwar, the Sarju flows across the stike of the different formations with curvatures and bends at a number of places. The subsequent nature of the tributaries of the Sarju river is evident from the map.

<u>Water falls</u>

Some water falls have been noticed in some subsequent streams of Sarju and in some insequent tributaries of the subsequent streams. No water fall is seen in the main river, Sarju. Along the Kaphauli-Balaldev-Chanapani streams at least 2 or 3 water falls may be seen varying in height from 15 to 30 ft. Some more smaller water falls may be seen at a number of localities, where the small streams fall from the hillocks.

<u>Geomorphic Inferences</u>

Geomorphically, the area represents an early mature stage of topography which is indicated by the following features:

a) Rounded topography (Plate VI Fig. 1)
b) Broadening of valleys
c) River meandering (Plate VI Fig. 1)
d) Development of hogbacks
e) Relief moderate to high
f) Lack of water falls.

<u>Climate and Rainfall</u>

In general, it can be said that the climate of this area is congenial. In summer, the maximum day temperature goes upto 25°C and the minimum temperature in the winters falls as low as -3°C. The order of the three seasons is the same as on the plains, the winter is almost without snowfall, summer of nearly tropical heat followed by a season of periodical rainfalls. Usually there is a slight rainfall during the winter season as well. In deep winter occasionally there is some snowfall at altitudes above 5,000 ft. The monsoon is usually confined to the June-September period. The most congenial periods for field work in this region are from early October to early December and early March to early June.

<u>Fauna, Flora and Inhabitants</u>

Some of the typical Himalayan vegetations are preponderant around the hilly areas of Bageshwar. Sal (<u>Shorea robusta</u>) and Tun (<u>Ecdrelatoona</u>) grow at an elevation of 4,000 ft. and above. The most luxuriant and economic plant of the area is chir (<u>Pinus longifolia</u>) which is more abundant in the reserve forests of Chhateena, Jualkande, Phalyanti, Jhatkwali, etc.

The forests are infested with wild animals such as leopards, black bears, wild dogs, etc. Among the reptiles Goah and snakes are common. The colourful birds of the Kumaon Himalayas had once been a subject of keen interest of Professor Salim Ali, a famous Indian ornithologist.

The area is thinly populated and the original inhabitants consist mostly of Brahmins, Thakurs, Sahs and Salapkars. They all speak in the local Kumaoni dialect.

Brief History of the Ancient Copper-Lead Industry

Earlier, copper and lead occurrences were reported from many localities in Almora, Pithoragarh and Chamoli districts and also in the Garhwal Himalayas, Uttar Pradesh. The existence of several ancient workings in most of thesea places indicates that once in the past there was a flourishing mining industry. During the reign of the Kumaoni and Gurkha rulers,[1] copper and lead were extensively mined at Almora (see Nautiyal, 1962). Some of the mines in this area were in operation till about 1874. Several attempts were made to revive the mines during the British rule, but practically without any success.

An extract of the information, provided by Lawder (see Nautiyal 1962, pp. 342, 349) regarding the production and utilization of copper in the Kharai Patti, within which lie the deposits of Balaldev (29°48'06", 79°45'11"), Dewaldhar (29°46'52", 79°45') and Belauna Sera (29°48'38", 79°46'33"), is given in the following table:

TABLE - I *

Year	How worked	Amount raised for private use (maunds*)	Amount of ore sold (maunds)	Amount of metal sold after melting ore (maunds)	Amount of metal exported (maunds)
1868	Deep shaft	-	2	-	6
1869	Deep shaft	1	13	9	10

* One maund = 37 kg. (approx.)

1 Later part of 18th century.

* Production and utilisation of copper in years 1868 and 1869.

Mining and Indigenous Smelting Methods

Stephens (see Swarup and Misra 1945, p.13) gave the following account of the mining methods applied by the ancient workers in the Kumaon-Garhwal region:

> The ancient underground works are of the rudest descriptions... The workmen did not understand attacking a deposit by shafts or levels and their natural desire was to burrow ... Timbering was of the weakest description -- a forked stick and a cross piece resting on the fork, or at most two forked sticks, one on each side of the working, with a "Cap" placed in the two forks ... If water was met with, the miners either formed a line and dropped it out passing the "deckshie" of earthern ware pot from hand to hand, or they included a number of bamboo troughs in a step like series... The native tools are imperfect in the extreme -- a soft iron pick, with no pole, about 1½ lbs. in weight, a small hammer and a few wedges.

About the ancient indigenous methods of smelting in Almora district, Nautiyal (1962, p. 356) stated that the ore was first crushed on hardstone slabs. The powder so obtained was mixed with cow dung and small rounded balls were made. These balls were dried for two or three days in the sun and then mixed with wood charcoal (from pine, oak,etc.) in the required quantity. This mixture was fired in a furnace where the slag would flow away. Ordinary bellows were used for blowing the air. The blister copper so obtained was subsequently fired and beaten into copper sheets. The details of the proportion of charcoal and ore used in smelting are not known.

Causes of the failure of Copper Industry

Stephens' (see Swarup and Misra 1945, p.13) description of the Almora deposits clearly indicates that the mining methods were of primitive fashion and the tools used were of inferior quality. This might have been one of the causes of the failure of the copper industry of Almora. Nautiyal (1962, p.356) suggested that the water trouble, inadequacy of funds and poor communication were other probable causes of failure of copper industry of the district.

PREVIOUS INVESTIGATIONS

Perhaps Strachey (1851) published for the first time the generalized geological maps and sections of the Kumaon Himalayas. His structure section shows the main sub-divisions of the Kumaon Himalayas.

Heim and Gansser (1939) took a number of traverses in the sub-Himalayas, Lower Himalayas, Higher and Tethys Himalayas of the Kumaon section. Their traverse maps included the present area and its geology in outline. The calcareous series in the north of Bageshwar was named as the calc zone of Chamoli and the calc zone south of Bageshwar was designated as the calc zone of Badolisera. The two calc zones were correlated with the Krol series of the Simla-Krol Himalayas (Permo-Triassic age). Heim and Gansser (1939) also reported a thick section of quartzites overlying the calc zones of Chamoli and Badolisera. They correlated these quartzites with the Tals (Jura-Cret.?) which overlie the Krols in the Krol-Simla belt. Gansser (1964), later modified his earlier views and correlated the calc zones of Chamoli and Badolisera with the Deoban limestones of Chakrata, north of Simla (upper Precambrian to lower Paleozoic age) and the quartzites with the Jaunsars (ordovician). Gansser (1964) believed the stratigraphic sequence in this metasedimentary belt to be in normal order.

Auden's (1934, 1937, 1939) main investigations were in the adjoining parts of the present area. Gansser (1964) has repeatedly appreciated the work of Auden in the Krol belt and Dhanpur-Garhwal region of the Kumaon Himalayas. Auden was perhaps the first to recognize the great magnitude of the crystalline thrust sheets of the Kumaon Himalayas.

Swarup and Misra (1945) gave an account of the ancient copper industry and also of the mineralogy of the copper slag collected from Dewaldhar area, Almora district. They reported the occurrence of chalcopyrite, cuprite, malachite and some azurite from the area.

Jhingran and Mathur (see Roy 1961, p.109), who carried out sampling for lead ore along a belt between Chhanapani (29°47'43", 79°44'56") and Belauna Sera are of the opinion that galena occurs as small stringers and disseminations which are scattered sporadically in the dolomites of the Garhwal series.

Subramanyam and Jain (1961, 1960a, 1960b, see Roy 1962, p.33 and 44) carried out geological and geochemical investigations in the Shishkhani (29°48'18", 79°44'54")-Chhanapani-Balaldev (79°48'06", 79°45'11") copper-lead belt. But unfortunately all of their publications are in the form of abstracts. According to Subramanyam and Jain (1961), the copper-lead mineralization in parts of Almora district is confined to one rock type, viz., a massive dolomite unit, the bedding and slip planes of which control the sulphide distribution.

Nautiyal (1962) for the first time described the geology of copper belt of the Almora and Pithoragarh Himalayas with a brief history of exploration and mining industry in ancient days. He also recommended Bora Ager (29°43', 80°03'30") deposits (Pithoragarh district) for further prospecting. He considers the Almora copper deposits to be of hydrothermal origin.

Rasul and Sharma (1963) for the first time made a casual ore microscopic study of the lead ores from Chhanapani, Almora district, and suggested that the deposits were of low temperature hydrothermal origin.

Misra and Valdiya (1961) restricted their study to the Pithoragarh district which is adjacent to Almora district. In the southern part of Pithoragarh, the massive formation of cherty, dolomitic and argillaceous limestones, including the stromatolitic limestone, shale and slate have been grouped by them as the "calc zone of Pithoragarh". Valdiya (1962a) described in some detail the stratigraphy and structure of the southern parts of Pithoragarh district and observed that the stratigraphic sequence of this metasedimentary zone is inverted. Gansser (1964), however, has not favoured this observation of Valdiya.

In the adjacent district of Chamoli, Dar (1964) reported the association of copper and uranium mineralization and regarded the deposits to be of low temperature hydrothermal origin.

Misra and Banerjee (1965, 1967) published two abstracts in which the geology and sedimentation around Bageshwar, district Almora, was discussed. They, however, excluded the mineralized belts of Shishkhani Chhanapani-Balaldev region of Bageshwar.

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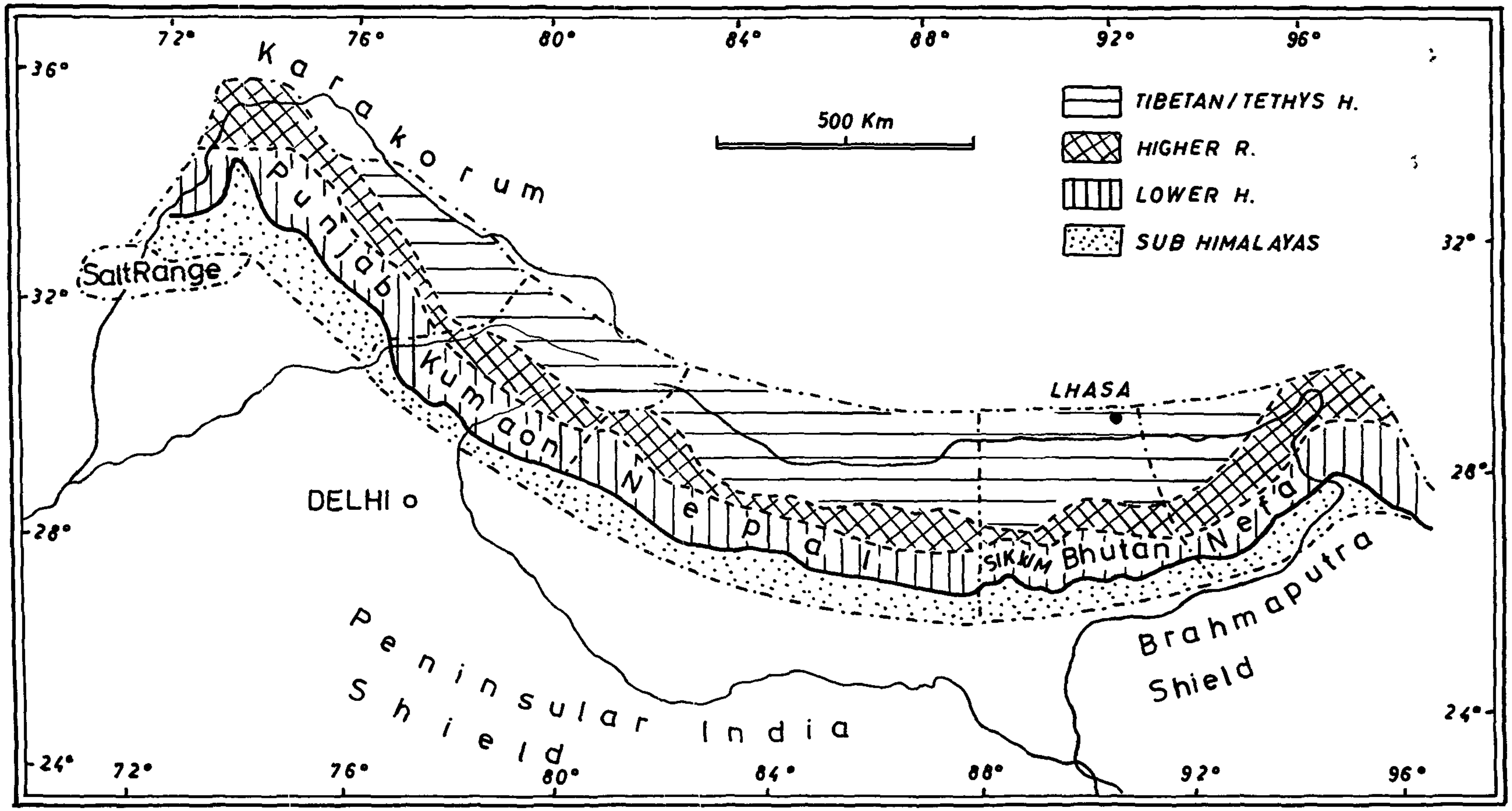

FIG.3. THE GENERAL SUBDIVISIONS OF THE HIMALAYAS

(AFTER A. GANSSER 1964)

Chapter - II

STRATIGRAPHY AND LITHOLOGY

A. Regional Geology and Stratigraphic Setting

The area under study forms a part of the Lower Himalayan subdivision of the Kumaon Himalayas (Fig. 3) which extend for about 320 kms. from the Sutlej river on the west to the Kali river on the east. The well-known peaks of the Kumaon Himalayas include Nanda Devi (7,816 m), Badrinath (7,069 m), Kedarnath (6,940 m), Trisul (7,120 m), Mana (7,273 m) and Gangotri (6,615 m).

About the tectonic complications in the Kumaon Himalayas, Gansser (1964, p.80) points out that "In spite of the considerable amount of work done already in the Kumaon Himalayas, this stretch of mountains is still dotted with unsolved problems and remains in my opinion, one of the most inspiring places of geology of our globe".

Reported from all along the foot-hill zone (sub-Himalayan region) of the Kumaon Himalayas, are the fluviatile tertiary deposits (Siwalik System) consisting of violet, red, green clays and sandstones which may be seen even upto Kathgodam, a locality at the base of the sub-Himalayan zone.

Geologically, the Lower Himalayas of Kumaon may be divided into the following zones and groups (see Gansser, 1964):

a) The Infra-Krol-Krol-Tal belt, stretching from the Sutlej river in the north-west to Nainital (29°23', 79°30') in the south east.

b) The Almora-Dudatoli and the Askot-Baijnath crystalline masses.

c) The inner sedimentary belts which include calc zones of Deoban, Tejam, Chamoli, Badolisera, Pithoragarh, etc.

d) The sedimentary zones which include the quartzites of Berinag, Chamoli, Nagthats, Jaunsars, etc.

As it was beyond the scope of the present study, no serious attempt was made to correlate the stratigraphic succession of the area with the other adjacent formations of the Himalayas. Moreover, Gansser (1964) in his recent work has already correlated the rocks of the area under review, with the adjoining formations in other parts of the Himalayas. The author found it convenient to divide the area geographically into south Bageshwar calc-zone and north Bageshwar calc-zone for the purpose of geological description. As a matter of fact, the south Bageshwar calc zone is nothing but a continuation of the Badolisera Calc Zone and the north Bageshwar Calc Zone is the same as the Chamoli Calc Zone of Gansser (1964, p.94-95). On similar grounds, the quartzites which were considered to be the western continuation of the Berinag quartzites (Valdiya, 1962) are described here as the Bageshwar quartzites.

Age Correlation

The stratigraphic correlation of the inner sedimentary belt of the Lower Kumaon Himalayas has been a subject of great controversy in Indian stratigraphy for the last three or four decades.

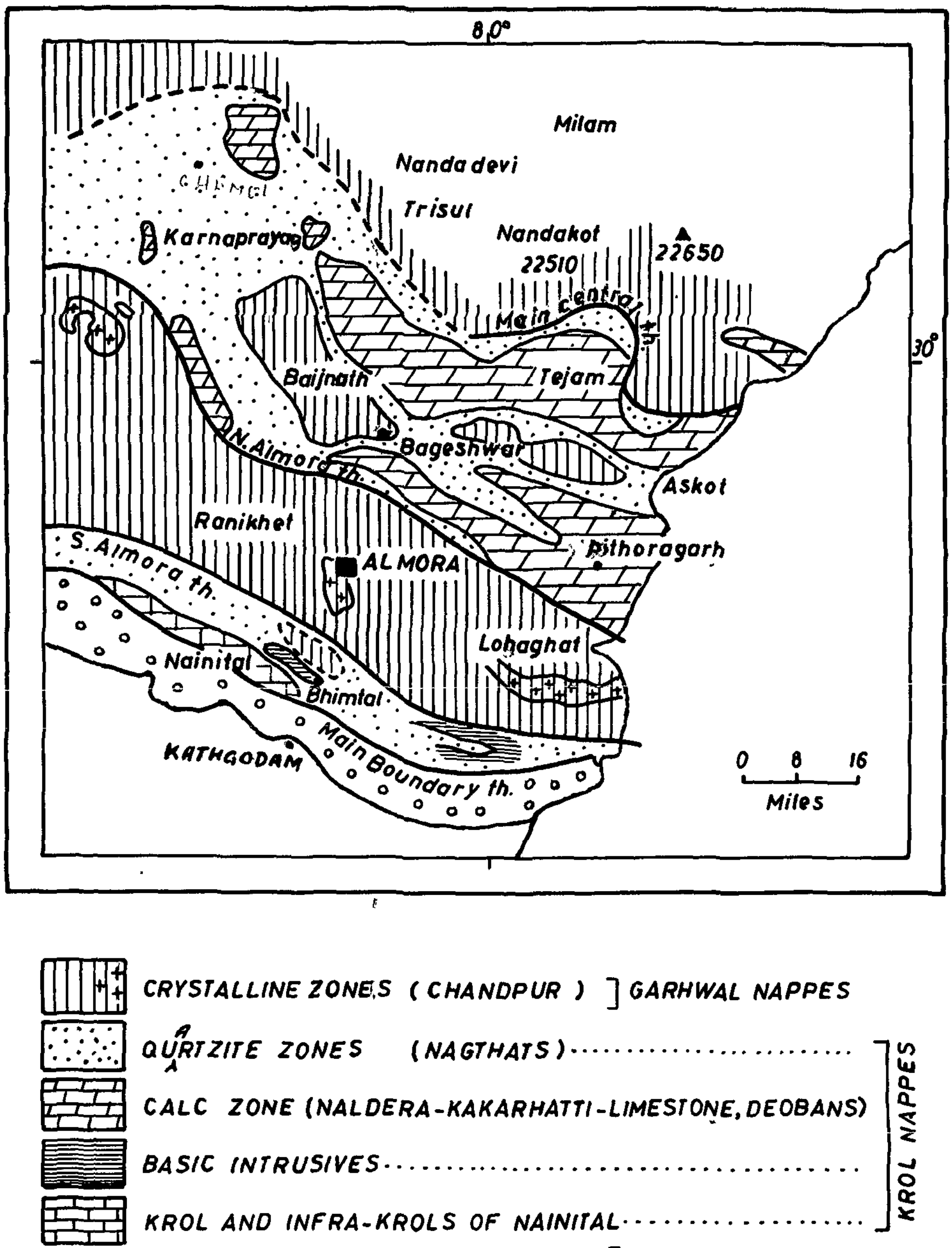

FIG. 4. REGIONAL TECTONIC MAP OF THE KUMAON HIMALAYAS (AFTER J.B. AUDEN; A. HEIM & A. GANSSER; AND K.S. VALDIYA)

Heim and Gansser (1939) after taking a number of traverses in the Kumaon Himalayas, were more inclined to correlate the inner sedimentary calc zones with the Krol limestones (Permo-Triassic) of Krol and Nainital regions. The quartzites were then correlated with the Tals, which overlie the Krol limestones in the Krol region. The above correlation was, however, suggested doubtfully.

After a lapse of about 30 years, Misra and Valdiya (1961) and Valdiya (1962a) made some valuable contribution to the stratigraphy, structure and tectonics of a section of the Kumaon Himalayas. They (1961) reported for the first time the occurrence of algal stromatolites (collenia) in the calc zone of Pithoragarh. Later on, Valdiya (1962b) reported similar algal structures from the Shali limestones of Simla. On the basis of the occurrence of algal stromatolites and the lithologic similarities Valdiya (1962a) correlated the calc zone of Pithoragarh with the Deoban limestones of Upper Precambrian to Lower Cambrian age. Gansser (1964, p.98) accepted this correlation of Valdiya and divided the Deoban-Tejam calc zones in the south-eastern Kumaon Himalayas into two belts viz., (1) the southern belt, made up of the Badolisera and the Pithoragarh calc zones and (2) the northern belt, made up of Chamoli and Tejam calc zones. The Badolisera calc zone is actually the western extension of the calc zone of Pithoragarh, and the Chamoli calc zone the westward continuation of the calc zone of Tejam. The two belts which include the calc zones of Badolisera-Pithoragarh and the calc zones of Chamoli-Tejam are separated by the Berinag quartzites at Pithoragarh and by the Bageshwar quartzites at Badolisera (Fig. 4). A thrust separates the Berinag and also the Bageshwar quartzites from the overlying gneisses and schists, introduced by Gansser (1964) as the Askot-Baijnath thrust.

Valdiya (1962a) correlated the Berinag quartzites with the Jaunsars (= Nagthats = Ordovician)of Simla. Gansser (1964, p.99) placed the Jaunsars above the Deoban limestones and he thus believed the stratigraphic sequence of the region to be normal with the older calc zones occupying a position below the younger quartzite zones. An age between the upper Precambrian and Lower Paleozoic was affixed by Gansser (1964) for the calc zones and the quartzites under review.

Heim and Gansser (1939), and Gansser (1964, pl.III) correlated the Askot-Baijnath crystallines with the Almora-Didotoli crystallines of the Precambrian age.

B. Stratigraphy and Lithology of the Area

General Statement:

In this section an attempt has been made to describe the lithology and distribution of the various rock types of the area under discussion. The chief lithological units are metamorphosed orthoquartzites, crystalline dolomitic limestones and altered carbonate rocks, crystalline shists and gneisses, etc. The orthoquartzites sometimes alternate with altered basic rocks (epidiorite) occurring in the form of sills. The outcrop pattern of the various lithologic units have distinctly been controlled by the structure and tectonics of the region. The structure of the area has been made more complicated owing to intense tectonic disturbances to which the Himalayan rocks were subjected during the tertiary period.

However, the rocks introduced above, could easily be recognised in the field by their variation in colour, grain size and mineralogical composition.

Stratigraphy

Lithologically, the more commonly encountered rocks of the area may broadly be grouped into the following three major types: (1) The calc zones of Bageshwar; (2) Bageshwar quartzites, and (3) Baijnath crystallines.

1) Calc Zones of Bageshwar - On the basis of their local geographic distribution, the calc zones of Bageshwar are subdivided into (a) north Bageshwar Calc zone and (b) south Bageshwar Calc zone. The north Bageshwar Calc zone is actually the westward continuation of the calc zone of Tejam and forms a part of the northern limb of the major syncline shown by Gansser (1964, section 2, plate III). The south Bageshwar Calc zone is supposed to be the westward continuation of the calc zone of the adjacent district of Pithoragarh. This zone lies south of the Bageshwar township and it falls within the southern limb of the same major syncline of Gansser (1964).

The Calc zones in the south as well as in the north of Bageshwar are essentially made up of several varieties of slates and carbonate rocks, as given below:

i) Slates
   (a) Dark carbonaceous slates
   (b) Purple and olive green slates
   (c) Graphitic slates
   (d) Calcareous slates
   (e) Black slates with sulphur encrustations and disseminated cubes of pyrite.

ii) Carbonate Rocks

The carbonate rocks conformably overlie the slates and the following lithologic types are distinguishable:

(a) Stromatolitic limestone
(b) Dolomites
(c) Talc-dolomite rock
(d) Thin bedded limestones with calc-phyllites, etc.

2) The Bageshwar Quartzites - The two calc zones in the Bageshwar area are laterally separated by a 4-5 mile wide zone of quartzites. These quartzites are believed to be the western continuation of the Berinag quartzites of Pithoragarh and they have been correlated with the Nagthat and Jaunsar series of the Garhwal and Punjab Himalayas by Valdiya (1965, 1962a).

Compositionally, they may be called orthoquartzites. Some bands of phyllites which occur as intercalations. Numerous basic sills are associated with these quartzites at a number of localities.

3) The Baijnath Crystallines - The Baijnath Crystallines occupy a wide syncline in the north of Bageshwar. These crystallines are made up of paragneisses, chlorite-schists, augen-gneisses, mylonites, phyllonites and some cataclasites. They overlie the Bageshwar quartzites with a thrusted contact.

Stratigraphic Sequence

The following stratigraphic sequence has been determined in the area:

Baijnath crystallines	5.	Augen gneisses, chlorite schists, mylonites, phyllonites, etc.
----------------- Baijnath Thrust -----------------		
Bageshwar Quartzites	4.	Quartzites with intercalated phyllites and intrusive basic sills.
Calc zones of Bageshwar	3.	Dolomite and talc-dolomite rock with copper and lead ores.
	2.	Algal stromatolitic limestone with thin-bedded limestones and calc-phyllites at the base.
	1.	Slates
		? Base unknown

Lithology

1. <u>Slates</u> - Slates are usually to be seen occupying the lowlying areas along the Sarju river and several creeks south of Bageshwar. North of Bageshwar, the Jhandi hill (5,800 ft.) is made up of slates. These slates, which are correlated with the Sor slates of Valdiya's (1966) calc zone of Pithoragarh, show a wide range of colour and composition. They are often black, olive green and purple in colour. Dark and white bands of carbonaceous and calcareous materials are also common, e.g., at Dafat Gad streamlet and Sarju river confluence (near Balauna Sera village) at Shishkhani, Chhanapani village, etc.

To the west of the Sarju river and a mile south of Bageshwar the slates are highly cleaved and flaggy. Another very important variety of this horizon is the black carbonaceous slate found both in the south and the north calc zones of Bageshwar. The dark carbonaceous slates are very well exposed in the main Dafat Gad stream, in the south Bageshwar calc zone and also near Doya (29°52'20"; 79°47'42") in the north Bageshwar calc zone. Near Jhatkwali (29°52'18"; 79°47'26") thin bands of sulphur occur along the slate partings. These sulphur bearing slates which extend northwesterly for about 150 yards near Jhatkwali, are also pyritic in nature and impart a reddish and yellowish surface on weathering.

Graphitic slates were found near the contact of the north Bageshwar calc zone and the Bageshwar quartzites, about 3 miles north of Bageshwar (near Baligad). Close to the faulted contact of the north Bageshwar calc zone and the Bageshwar quartzite near Ghirauli (29°52'02"; 79°47'18"), the slates grade upward into phyllites. Beautiful specimens of fault breccia (Plate IV, Fig.2) showing fragments of slates in a calcareous matrix have been collected from a number of localities such as Ghirauli, Chhana (29°53'; 79°46'54"), Tamkhani (29° 53' ; 79°46'32").Generally, slates are intensly folded and faulted throughout the region. Complex minor folding (Plate IV, Fig. 3) and dislocation' is common near Belauna Sera, Dafat Gad stream-Sarju river confluence, and also near Baligad (29°52'30"; 79°46'50"), Doya, etc.

The slates are very frequently used as building stones in Bageshwar and its surrounding localities. A small quarry is still in operation near Chhanapani village.

2. Algal stromatolitic limestone with thin-bedded limestones and calc-phyllites -

Thin bedded limestones and calc phyllites directly overlie the slates. But due to faulting and erosion outcrops of these limestones are missing from many localities. Varying in colour from white, pink to purple and grey, these limestones are very well exposed at Belauna Sera, Bergaon (29°48'; 79°45'05"), Raikholi (29°47'42"; 79°46'54"), Pandidhar

($29^{\circ}48'$; $79^{\circ}46'30''$), Sarma Reserve Forest, etc. These rocks have also been recorded at Chhana, Jhathwali reserve forests and several other localities in the north Bageshwar calc zone. The contact between the thinly bedded limestone and the algal limestone is difficult to demarcate as it is irregular and somewhat gradational.

Structurally, these limestones show evidence of intense deformation (Plate IV. Fig. 1). Minor folding and faulting are very common at the localities mentioned above. Jointing is common in all these limestones. Along some of the master joints, recent calcareous deposits such as tufa, stalactites, stalagmites, etc. are formed.

The dolomitic limestones with algal stromatolites conformably overlie the calcareous phyllites and slates. The algal stromatolitic limestones have been recorded from several localities. Some good exposures were located about a mile south of the town limit of Bageshwar, west of the Sarju river bend. The algal stromatolites occur as concavo-convex laminae. and laterally linked hemispheroidal bodies in the form of folds (Plate I, Fig. 4). Logan, Rezak and Ginsberg (1964) recognised similar concave-convex laminae as the genus collenia. The other important localities where such algal stromatolites occur are: Baligad, Kaphauli ($29^{\circ}48'12''$ $79^{\circ}45'45''$), Kaligad ($29^{\circ}48'58''$; $79^{\circ}46'54''$), Tupar ($29^{\circ}52'$; $79^{\circ}48'48''$), Baldori ($29^{\circ}52'42''$; $79^{\circ}48'48''$) etc. On weathering, pink laminae of the stromatolites give rise to a reddish coating on the limestone surface.

Only on the basis of the occurrence of algal stromatolite in the Shali limestone as well as in the calc zone of Pithoragarh, Valdiya

(1962, 1965) and Gansser (1964) correlated both of them with Deoban limestones of Upper Precambrian to Cambrian age. The presence of algal stromatolites in the north as well as south of Bageshwar, therefore, further strengthens the view that the area is the western continuation of Pithoragarh calc zone as well as of the calc zone of Tejam.

Therefore, on the basis of the occurrence of algal stromatolites in the dolomitic limestones of south and north Calc zones of Bageshwar, the age of the formation may also accordingly be placed between Upper Precambrian and lower Cambrian.

These dolomitic limestones are medium to fine grained with numerous closely spaced lenticular cherty bands. Due to differential weathering the cherty bands stand out as 4 to 6 inches high corrugations on the outcropping surface of these limestones (Plate I, Fig.1). The limestones also display a typical elephant skin weathering (Plate II, Fig. 1). Rhombohedral joint pattern is frequently seen in these limestones (Plate I, Fig.2).

3. Dolomites, Talc-dolomite Rocks and Silicified dolomitic limestone with copper and lead ores -

The stromatolitic limestones pass imperceptibly upwards into dolomites, talc-dolomite rocks, dolomitic limestones and silicified dolomitic limestone. At some places these carbonates directly overlie the slates and the calc phyllites without any intermediate zone of the stromatolitic limestones. The wide variation in composition and texture of the carbonate rocks of this horizon is mainly due to the effect of continued hydrothermal activity which may also be held responsible for the deposition of copper and lead in this region. The mineralisation of copper and lead is confined mainly to the dolomites, talc dolomite rocks, talc schists and the silicified dolomitic limestone, in the copper-lead belt of Shishkhani-Chhannapani-Balaldev; as also at Ghirauli, Tamkhoni, Malta (29°49'; 79°47'56"), Dewaldhar, etc. The rock group shows a wide variation in texture and composition not only from one outcrop to the other, but also within the same outcrop. For example in Balaldev-Shishkhani-Chhanapani region the copper ores are associated closely with the coarse grained dolomite, talc dolomite rock and talc-schist, whereas the barren country rock outside the limits of mineralized zone, even in the same outcrop, is fine-grained in texture with lower dolomite content. One more striking feature is that the ore-laden dolomites are light coloured, whereas the barren limestones are grey, dark grey and even black in colour. Galena was found in the silicified dolomitic limestone at Pur Shishkhani (29°48'15"; 79°45'18"), Chhanapani and the south of Balaldev ridge (29°47'58"; 79°45'06"). Silicification is indicated mainly by the replacement of the carbonate minerals by jasperoid and partly by the veining of the carbonates by quartz. Galena occurs either as vein mineral filling the fractures in dolomite or as disseminations in the silifified portion of the dolomitic limestones.

4. Quartzites - Conformably overlying the carbonate rocks of the south and north Bageshwar calc zones, are the Bageshwar quartzites with some basic sills and intercalated phyllites. They are well exposed around Bageshwar, Jaulkande (29°49'06"; 79°45'05"), Rangers Quarter (29°49'58"; 79°45'30"), Kuirali (29°50'30"; 79°48'48"), Chhati (29°48'48"; 79°48'18"), Chhateena (29°49'24"; 79°47'30"), Mankot (29°49'54"; 79°49'), etc., and also in the catchment areas of Amsiarikot Gad, Joshigaon main stream and numerous other

streamlets.

The quartzites are pink, white and light yellow in colour with medium to fine grained texture. In general, they are orthoquartzitic, although at some places near Bageshwar these quartzites appear to be schistose.

All over the area they are highly jointed (Plate III, Fig.1) and sometimes it is rather confusing to distinguish between the bedding planes and joint planes of the rocks in the field. Primary sedimentary structures such as ripple marks, (Plate I, Fig.3), cross bedding (Plate III, Fig.3) and graded bedding have been recorded in the quartzites from a number of localities.

The quartzites are occasionally intercalated with bands of phyllites such as recorded from Jualkande, Gomati river outcrops at Bageshwar, Joshigaon (29°51'12"; 79°47'18"), Ara (29°51'48"; 79°46'08"), etc. The basic sills which occasionally alternate with the quartzites are distributed all over the area. They may be seen at a number of places along the Bageshwar-Garur and the Bageshwar-Jaulkande Reserve Forest foot tracks, along the Jaulkande-Borgaon foot track, Amsiarikot Gad, Chhateena, Chhati, Chami, etc. These basic sills are mostly altered into epidiorites. No dyke was however, recorded.

5. <u>Baijnath Crystalline Zone</u> - The Baijnath crystallines overlie the quartzites of Bageshwar with probable thrusted contact. The rocks pass through Kathathbara (29°51'; 79°46'54") and extend beyond the eastern banks of the Serju river about 5 miles northwest of Bageshwar.

The crystallines are represented by augen gneisses, chalorite schists, mylonites, phyllonites, pink felspathic schists, etc. The chlorite-schists are well exposed around Kathathbara and along the Sarju river. In the Khabdoli south reserve forest augen-gneisses and pink felspathic schists are predominant. The outcrops in the northwest of Kathathbara are very scarce and irregularly distributed. The weathering of the crystallines at Kathathbara, Joshigaon, Mandal Sera regions gave rise to a type of red residual soil.

Quartz veins are common in these schistose rocks at Kathathbara and Joshigaon (PlateIII, Fig.2). The schists are highly folded and faulted more conspicuously near the bend of the Kathathbara-Mandal Sera syncline (Plate V, Fig.2).

Chapter - III

STRUCTURE AND MORPHOTECTONICS

STRUCTURE

The author, in course of the present investigation, also made an attempt to know something about the structural setting of the area without going much into the details of the subject. The study is largely based on the geological map (Fig. 5) in which only those structural data were recorded which have some bearing on the nature and trends of such structures as folds, faults and some systematic joints. The purpose of this work was simply to bring forward for the first time, the pattern of the various outcroping rocks and their structural relations. The author also believes that there is a great scope for more advanced work on the tectonics and structure of this Himalayan terrain.

The topographical set up of the various lithologic units at Bageshwar is closely related to the structure. This has been discribed later in this chapter. The major structural trend in Bageshwar is northwesterly which is in close harmony with the general trend of the Himalayas in this region.

Due to repeated orogenic movements during the tertiary, the structure of the Himalayas were made highly complicated. Krishnan (1960) and

Krishna Swamy and Swaminathan (1965) distinguished four major impulses of the Himalayan orogeny due to which the earlier structures were affected by the later movements with the result that the earlier ones in some areas have been completely obliterated.

The investigator made full use of the 'background' knowledge of Himalayan tectonics available from many of the earlier published works. In order to have a better idea of the regional geological and structural setting, the writer in course of his work visited some of the neighbouring areas like Jhiroli (29°46', 79°45'), Bora Agar (29°43', 80°03'30") and Garur.

The various structural elements have been divided into the following two genetic units: A. Non-diastrophic or sedimentary, B. Tectonic or diastrophic.

A. Non-diastrophic Structures

1. Bedding

The bedding or original stratification (S_1) was the first planar structure developed at the time of deposition. The limestones, quartzites and slates are characterized by the presence of distinct bedding planes. The S_1 planes in these rocks may partly be recognised by their distinctly bedded nature and partly by the colour contrasts of the stratification bands particularly in the slates. However, the recognition of bedding planes in the slates sometimes pose a problem. But generally, the bedding lamination in slates are also recognized by their alternating white (calcareous) and dark (carbonaceous) colours. The calcareous phyllites have also bedding laminations which are coloured differently and the more common colours are white, pink or grey.

In the limestones the bedding partings may be identified by innumerable alternating bands of chert. These resistant bands project 4 mm to 5 or 6 mm. above the limestone due to the differential weathering of the rock (see Plate I Fig. 1). Sometimes, when the bands are of different colours, it becomes easier to distinguish the bedding planes in limestones.

The quartzites are generally thick bedded. Due to the presence of three sets of systematic joints in the quartzites, sometimes the joint planes are mistaken for bedding planes. However, with a little care and experience the bedding planes could be identified in most of the quartzites especially, those having either intercalations of phyllites or their bedding planes coloured differently.

2. Cross Bedding

Cross-bedded quartzites were recorded from many localities such as Bageshwar, Joshigaon, Shish-khani, Jaulkande reserve forest, Ghirauli, etc. Special care was taken to determine the attitude of these cross-beds in order to find out the top and bottom of the quartzites. In all these localities mentioned above, the cross beds give no idea that the quartzites are inverted anywhere.

3. Graded Bedding

This sedimentary character of the rocks results due to the variation in the size of the grains of which the bed is composed. In normal situations, gradation is from coarser material below to finer above. The outcrops of Bageshwar quartzites at Gomati bridge, Ghirauli, etc. display a normal gradation in the size of quartz grains.

4. Ripple Marks

The quartzite occurring at Shishkhet, Jaulkande reserve forest, Joshigaon streamlet exposures, etc. are occasionally ripple-marked (Plate I Fig. 3). They were identified as current ripples because of their asymmetric nature. The normal order of the quartzites was also indicated by the position of the ripple-marks in relation to the bedding planes.

B. Tectonics or Diastrophic Structures

General Statement

Among the various diastrophic structures mention may be made of folds, faults and joints which are more common and conspicuous in the area.

The study of major structures of a small area, as in the present case, as compared to that of the gigantic Himalayas will evidently not give a full and clear picture of the structure of the area. Obviously this problem can be tackled well only when a larger section is surveyed from this point of view. Fortunately, geological mapping of about an area of 55 sq. miles around Bageshwar included a refolded major syncline, the central part of which consists of the southeastern sector of the Baijnath crystallines and the rest of the area is made up of a conformable and normal sequence of slates, limestones and quartzites, all of which are highly folded and also affected by several faults.

1. Folds

Generally, the smaller and individual folds are characterized by broad synclines and narrow anticlines trending NW-SE and plunging northwesterly. The individual folds in most instances could be traced for long distances because of the continuity of the outcrops. For the sake of easy recognition the conspicuous folds are introduced after the names of the localities at or near which their axial traces were encountered.

a) Bageshwar Syncline: The axial trace of this syncline (Fig. 5) extends in a NW-SE direction passing through the localities Kathathbara, Mandal Sera and Kalasa. The southwestern limb of this syncline extends upto Dewaldhar where the general dip is to the north and north-east. The northeastern limb of this syncline extends upto Jhandi where the general dip is to the south and south-west. The plunge of the syncline is about 20°NW. The central part of this syncline is largely occupied by the thrusted schistose formations. This schistose formation is surrounded by the quartzites, and the slates and limestones are exposed on either sides of the quartzites. All these formations have their closures on the south-east which partly falls beyond the area on the eastern side. This is also an indication of the presence of a regional syncline plunging northwest. A few more evidence in support of a north-west plunge of this syncline are given below:

1. The minor folds near Belauna Sera (Plate II Fig. 2), Amarsa (Plate VI Fig. 2), Joshigaon, Phalyanti reserve forest etc. generally show a trend of NW-SE with 35 to 40° northwesterly plunge.
2. The contacts of slates and limestones also plunge in a north-westerly direction at a number of localities, e.g., at Kaligad, one mile south of Bageshwar (Plate V Fig. 1).

b) Kathathbara Syncline: The Kathathbara syncline has largely been occupied by crystalline schists and gneisses. The southern limb of this syncline has a general dip of about 60° NE and NNE, while the northern limb dips gently towards WSW and SW. The syncline closes southeastwards about one mile east of Bageshwar. Near its closure a bifurcation of the outcrop was also recorded.

The axis of this syncline passes through the localities, Kathathbara and Mandal Sera with a plunge of about 20° towards NW.

c) <u>Gomati Anticline</u>: On the north of the Gomati river, the quartzites dip 50 to 55° NNE. About 100 yards south of the Gomati, the dip in quartzite changes to 75° WSW. This indicates an anticline with its axis running roughly along the river valley. The plunge of this anticline is also northwesterly. This anticline appears to be a counterpart of the Kathathbara syncline and is traceable upto about one mile west of Bageshwar.

d) <u>Kaphlikhet Syncline</u>: Further south of the Gomati anticline, another syncline was encountered. Its axis runs NW-SE and plunges 35° northwesterly. There is an alluvial plane in the Kaphlikhet-Baret area where this syncline closes.

e) <u>Ghirauli Syncline</u>: This is another sycline in the north Bageshwar calc zone. The southwesterly dipping northern limb of this syncline is, however, much wider than the northeasterly dipping southern limb. The axis of this syncline runs NW-SE, but due to faulting near Baligad, its continuity has been broken. There are good field evidences to show that this syncline closes on itself on the north-west (i.e., NW of Baligad, in the Jhatkwali reserve forest) where the beds plunge 40 to 45° SE. This has been interpreted to mean that the plunge is inverted.

f) <u>Chhana Anticline</u>: About 3 miles north of Bageshwar (north of Lahor stream) an anticline was encountered. Due to axial plane faulting and subsequent erosion, a part of the southwestern limb of this anticline (south of the locality Ghirauli) is missing. The anticline however, is well exposed further north-west, near Chhana and Tamkhani and its axis runs roughly NW-SE.

g) Sarju Valley Anticline: Another anticline, the axis of which runs more or less along the Sarju river, on the south of Bageshwar, is evident from the geological map. There are several minor faults along the anticlinal axis. On the eastern side of the Sarju river the general dip of the slates, limestones and quartzites is northeasterly, but on the western side of the same river, the slates, limestones and quartzites dip WNW and NW. The axis of this anticline runs roughly NNW-SSE with a plunge towards the northwest.

2. Faults

A number of faults have been distinguished in the present area mainly from the occurrence of (1) conspicuous stratigraphic and structural breaks; (2) characteristic fault valleys and other typical topographic expressions; (3) fault breccia; (4) silicified zones. Only those faults in which one or the other of the above features are conspicudus, were recorded (Fig. 5). Longitudinal and transverse faults are more common.

a) Kathathbara-Kalana Dislocations: This is the major thrust fault in the area. The thrust sheet of the crystallines strikes NW-SE (see Figs. 5 and 6) and overlies the quartzites. Roughly the thrust, being a part of the Baijnath thrust, shows parallelism with the regional strike of the region. It contiues for about 20 miles beyond the north-west limit of the mapped area.

b) Ghirauli Fault: Another important fault runs NW-SE along a streamlet south of Ghirauli. This is an example of longitudinal fault. This fault, actually runs along the axis of an anticlinal fold (see Figs. 5, 6). The south-eastern part of this fault continues irregularly towards northeast upto Pungar river. Fault breccia has been located all through the faulted contacts of the rocks involved.

c) Faults Along Sarju River: A number of minor faults have been recorded from along the Sarju river. The faults occurring north of Bageshwar are more conspicuous in the neighbourhood of Baligad and further south (see Fig. 5). In the south Bageshwar calc zone, faults along the course of Sarju river are more frequent in Kaligad, Pagna, Kalauta, Pagnakhol and Ghuseti localities. The Sarju river flows for some distance further south along the faulted contacts between the slates and limestones.

d) Tanera Fault: About 1½ mile south of Bageshwar just south of Sarju river bend, a transverse fault striking ENE-WSW was recorded. It is marked by the presence of fault breccia, jointing and drags near the fault (Plate IV, Fig. 2).

e) South Kaligad Faults: In the south Bageshwar calc zone, between the localities Kaligad and Ghuseti (all along the Sarju river), there are at least four or five northeast-southwesterly running parallel faults. The general dip of the slate-limestone formation in this part is 45 to 50° NE.

f) Malta-Naugaon Fault: Another important longitudinal fault in the south of Bageshwar is that one which passes through the localities Malta, Naugaon, etc. This fault runs roughly NW-SE and probably extends further to the east beyond the boundaries of the area. Local dislocations near Malta and Dafat Gad were also recorded.

g) Shish-khani-Chhanapani Faults: In the Shish-khani-Channapani-Balaldev region, a number of local faults have been recorded. Most of them occur along streamlets and the faults occur mainly in the limestone and slate which consistantly dip north westwards. Some of the faults of this region have been demarcated on the map and they were recognised by the presence of fault breccia, slickensides and fault scarps.

h) South Jhatkwali Faults: In the north Bageshwar calc zone, south and east of the locality, Jhatkwali, there are two or three major dip faults which are conspicuous by their lithologic and structural breaks; and also by the presence of fault breccia. These fault traces roughly run NE-SW.

Besides the major faults enumerated above the area has been disturbed by a number of minor faults which approximately run in E-W or NE-SW directions. They generally follow small streams and creeks. It is interesting that some of the major axes of folds have parallelism with the attitude (NW-SE) of faults, indicating their tectonic relations.

3. Joints

Almost all the rock types of the area are jointed. The attitude of the systematic joints particularly in the quartzites and limestones have been carefully recorded throughout the region. Joints are however very well represented in hard and resistant rocks of the area, especially in the quartzites. Probably due to the chemical action of weathering, jointing in limestones has been obscured. Sometimes the outcrops of limestones exhibit rhombohedral jointing (Plate I, Fig. 2). Quartzites, on the other hand, are highly jointed (Plate III, Fig. 1) and sometimes, they break into smaller or larger blocks and slabs, due to the intersection of several joint planes. In the quartzites, generally the joints are of considerable length ranging from several meters to hundreds of meters. Mostly their joint planes are smooth and dip at high angles ranging from 65 to 90°. Depending upon the structures involved, the attitude of joints vary from locality to locality.

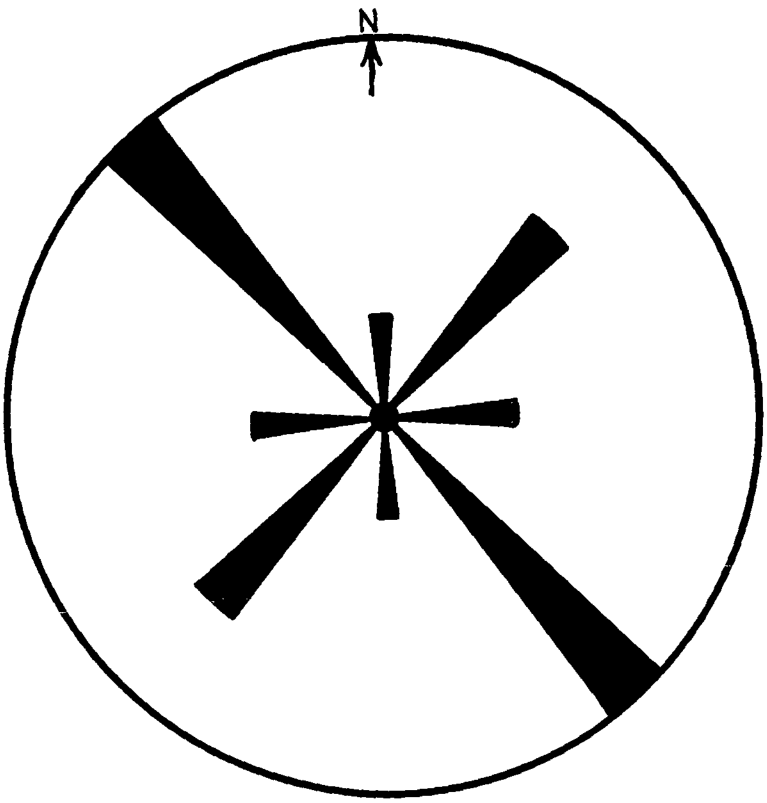

FIG. 7 STRIKE FREQUENCY OF JOINTS IN THE ROCKS AROUND BAGESHWAR

In general, the joints of the area may be classified into the following three kinds:

(a) The joints running more or less parallel to the folds were identified as longitudinal joints, the general trend of which are NW-SE. The joint frequency diagram (Fig. 7) clearly indicates that this trend of jointing is fairly common in the present area and is tectonically related to the fold system trending NW-SE.

(b) The NE-SW trend is another important joint set observed in the quartzites and the underlying rocks. This trend is thus, perpendicular to the general trend of folds and hence, it may be classified as cross joints. The joint frequency diagram (Fig. 7) indicates that the NE-SW trend is the second major joint pattern in the rocks of this region.

(c) The joints trending E-W and N-S were identified as diagonal joints in this area. These set of joints are also represented in the frequency diagram.

MORPHOTECTONICS

An attempt is made here to study the probable control of structure on the topographic expression of the area. Some relationships between faults and scarps, faults and the course of rivers and streamlets, faults and gorges, attitude of the formations and the course of streams. The axial trace of anticlines and the course of streams, plunge of major folds and the curvature in river course were recorded during the course of field investigations. These relationships are described below:

A. Faults and Scarps

Scarps were recorded at a number of places. Some of the important ones are, the Belauna Sera scarp, the Kaphauli-Balaldeo Scarp, Phalyanti stream scarp, etc.

The scarps may genetically be classifed into (a) fault scarp and (b) composite scarp (see Thornbury 1954).

1. Belauna Sera Scarp: The Belauna Sera scarp is probably an example of a fault scarp. On both sides of the fault, i.e., on the down thrown side and on the escarpment side calcareous phyllites are exposed. The fault runs along a streamlet at the base of the scarp. (Plate VI, Fig. 4).

2. Kaphauli-Balaldev Scarp: While moving along the Kaphauli Balaldeo Creek, small scarps have been observed at two or three places. They are characteristically fault scarps as they show most of those features which were seen at Belauna Sera.

3. Joshigaon Stream Scarp: A scarp, extending for about one mile along the strike of the quartzites (i.e., NW-SE) is conspicuous at the Joshigaon stream. This escarpment was also interpreted as due to faulting. On the facing side of the scarp is an alluvial flat. This scarp may be classified as a composite scarp. Another example of composite scarp is the escarpment near the Sarju river bend, one mile south of Bageshwar (Plate V, Fig. 3).

B. Faults and the Course of Rivers and Streams:

At a number of places the straight courses of some streams and the Sarju river were controlled by faults (see Fig. 5). Near Joshigaon, Deya, Baligad, Tuper, Khaldori, Ghirauli, Kaligad, Shishkhani, Dafat Gad, etc., this relation is very well marked. The fault which runs through Joshigaon, Kaligad, Kalauta and Ghuseti has controlled the course of the Sarju river in that sector.

C. Faults and Gorges

Sometimes gorges were formed along the fault zones. These features are common along the Sarju river at Kalauta, Pagna Khol, Pagna and also in the streamlets of Shishkhani, Balaldev region,etc.

D. Attitude of the Formations and the Course of Streams

Some distinct relationship appears to exist between the course of some streams and the attitude of the different geological formations. Most of the tributaries of the Sarju river follow the strike of the rock formations. These streams may thus be classified as the strike streams. Examples of such cases are: Joshigaon main stream, Chhati-Chhateena streams, the Pungar river, Lahor stream, etc. Phyllites which are intercalated with the quartzites are very well exposed in the stream bed of Pungar and Joshigaon. All the above streams roughly run northwesterly.

Another set of streams that follow the strike of the quartzites run northeasterly at Chami, Koerali and Amsiarikot Gad.

E. The Anticlinal Axis of Folds and the Course of Streams/Rivers

Some streams follow the axial region of the anticlines. The Gomati river near Bageshwar closely follows the axis of an anticline. In the south of Bageshwar, the Sarju river closely follows the axis of another anticline. A good number of such streamlets may be seen along the foot-track passing through Belauna Sera-Chaugaon Chinna-Dewaldhar.

F. Inter-section of divergent trends and the development of broad alluvial flats

The major syncline of Kathathbara in the northeast of Bageshwar that extends upto the Bageshwar town area is marked by a broad alluvial flat, famous for its cultivation in whole of this region. This semi-circular alluvial flat covers an area of about 2.5 sq. miles. The author believes that this broad trough was formed due to the intersection of three divergent trends in Mandal Sera-Kathathpara region (Plate VI, Fig. 1).

Chapter - IV

PETROGRAPHY AND PETROGENESIS

A. Carbonate Rocks

A detailed microscopic description of the various petrographic types of limestone and dolomite in which the copper and lead ores occur, is given herewith. Their depositional environment is also described briefly. Chiefly based on the presence or absence of the copper and/or lead ores, the host rocks are divided into the following two broad groups: (1) Mineralized carbonate rocks, (2) Barren carbonate rocks. Again, based on the texture and mineralogical composition, each group is further sub-divided into various subgroups and varieties:

1. Mineralized Carbonate Rocks

At Bageshwar the mineralization of copper and lead was observed in two distinct types of carbonate rocks, viz., a) Lead bearing limestones and b) Copper bearing limestones and dolomites.

a) Lead bearing limestones: On the basis of their mineralogical composition, lead bearing limestones may be defined as the silicified dolomitic limestones which were typically encountered in the Shish-khani and Chhanapani lead belt. There are veins of galena and also of cryptocrystalline silica in these limestones which vary considerably in their composition and texture. These variations are discernible not only from one locality to the other but also within a single locality. Even a rock specimen collected from a particular outcrop shows such textural and mineralogical disparities that are usually seen only in thin sections.

Microchemical test : It is practically impossible to differentiate dolomite from calcite by their optical properties. Microchemical test is the only reliable criterion for the determination of dolomites (see Canal, 1947; Friedman, 1959). Otto's test was performed to differentiate the two carbonates, since it is known to be one of the most reliable test for identifying dolomites (see Krumbien and Pettijohn, 1938). An uncovered thin section of the limestone was dipped in a 10 per cent solution of $AgNO_3$ for three minutes and after rinsing the section throughly with distilled water, it was again dipped in a neutral solution of K_2CrO_4 for a minute. After washing well with distilled water, the section was dried and subsequently covered. As a result this chemical processing those crystal sections, which were coloured brownish red, were confirmed as of calcite, whereas those which did not suffer any change of their colour, were identified as dolomite. About ten thin sections of the dolomitic limestones were tested by this method. The most distinguishing features of dolomite and calcite confirmed after the Otto's test are:

(1) Dolomites always occur as porphyrotopes set in a fine-grained calcitic matrix (Plate VII, Fig. 1,2); and (2) usually show euhedral rhombic form with-well defined twinning and rhombohedral cleavage -- a characteristic of the mineral. Calcite is freqmently very fine-grained and anhedral.

Mineral Constituents: Calcite, dolomite and silica, including its cryptocrystalline variety, jasperoid are the predominent constituents of these limestones. Galena is the only opaque mineral occurring either as veins or disseminations in these rocks.

1) Calcite : Calcite is frequently very fine-grained. It could be observed clearly as of brownish colour only after closing the iris diaphragm. Sometimes, the calcite crystals are interlocked with quartz. Silicification of calcite was beautifully displayed in most of the thin sections. The boundary between the cryptocrystalline silica and calcite is not sharp and very commonly it shows 'eating away' phenomena, an indication of replacement (Plate VII, Figs. 3,4). Fibrous secondary calcite often occupies the microvugs in limestones. Finer grained portions of calcite are dense and compact.

2) Dolomite : Dolomite is usually coarse-grained and occurs as porphyroblasts in a fine-grained calcite mass. The porphyroblasts are in the form of euhedral to subhedral rhombs with well-defined rhombohedral cleavage and twinning.

The textural relationship between calcite and dolomite is interesting. Always, calcite unlike dolomite tends to be anhedral (Plate VIII, Figs.1,2). The idiotopic dolomite crystals are loosely welded to one another. Often, dolomite, like calcite was replaced by jasperoid (Plate VIII, Fig.3). Dolomites have numerous microveins and microvoids which were later filled up by secondary fibrous calcite and more frequently by cryptocrystalline silica jaspereid (Plate VIII, Fig. 4 and Plate IX, Figs. 1,2). In these microveins and microvoids, at times, relicts of calcite and dolomite are also seen in jasperoid.

The replacement is pseudomorphic as well as partial in which case isolated fragments of dolomite lie embedded in silica.

3) Silica : Silica, both crystalline and cryptocrystalline, appears to be one of the most important constituents in these limestones.

Quartz,being the crystalline variety of silica, is interlocked with calcite and shows strain shadows. The quartz neither replaces nor being replaced by any mineral present in the limestones. The absence of any replacement and the interlocking nature of this quartz with the primary calcite suggests that the former is also of primary origin. It is clean, transparent and shows first order polarization colours. This variety of silica is not as abundant as that of the cryptocrystalline one. Hardly, it amounts to 5 to 6 per cent in these limestones.

Jasperoid : A special feature of these limestones is the high percentage of jasperoid, a cryptocrystalline variety of silica. Its association with the lead ore is more intimate (Plate IX, Figs. 3, 4 and Plate X, Fig. 1). According to Spurr (1908, see Schwartz 1955, p. 309) jasperoid is "a rock consisting essentially of cryptocrystalline chalcedonic or pheno-crystalline (phenairo-crystalline) silica, which has formed by the replacement of some other mineral, ordinarily calcite or dolomite". Lovering (1962, p. 862) restricted the definition of jasperoid to epigenetic silicious bodies formed largely by replacement, generally from hydrothermal solutions. Bastin (1951) also applied the term 'jasperoid' for the cryptocrystalline silica deposited by replacement of limestone and dolomite in the Tri-State Lead-Zinc district. The usage of the term 'jasperoid' as a mineral, is also common (see Lovering 1949, p. 28; Park Jr. and MacDiarmid, 1964, p. 58).

Jasperoid is grey in colour and microcrystalline. It very frequently replaces both calcite and dolomite (Plate X, Fig. 2) in thin sections of lead bearing limestones. There are also some replacing veins of jasperoid in the carbonate minerals. The jasperoid that shows vein replacement is commonly coarser than the one replacing the carbonate minerals. The two jasperoids viz., coarse and fine-grained are probably of the same generation.

4) Galena : Galena is the only opaque mineral constituent present in these silicified dolomitic limestones. It occurs intimately associated with jasperoid in veins (Plate IX, Fig. 3), and also irregularly disseminated aggregates. However, vein filling was more common than the disseminations. The details of textural relations between galena and jasperoid have further been discussed in chapter. VI.

Textures, Micro-structures And Their Interpretations

In general, the texture of these limestones may be said to be porphyrotopic (Friedman's terminology, 1965). The replacement texture is indicated by the following features:

1. The porphyrotopics of dolomite set in a fine-grained calcite matrix indicate replacement of calcite by dolomite, a feature observed earlier by Hewett (1928), Carozzy (1960), Murray (1960), Friedman (1965), Friedman and Sanders (1967, p. 295) in several carbonate rocks of other countries.

2. Numerous relict grains of calcite and dolomite are found in jasperoid perhaps because of incomplete replacement of the carbonate minerals by the latter.

3. In the majority of cases, contacts between certain minerals like calcite and dolomite, calcite and jasperoid, dolomite and jasperoid were found to be irregular and ragged displaying 'eating away' phenomenon which is one of the salient characteristics of replacement.

4. The rhombic shape, a characteristic crystal form of dolomite, has been retained by some jasperoids in a few veins. Such texture is described as the complete pseudomorph by Grout (1946).

The textural symbol of the jasperoidized portions of these carbonate rocks may be expressed as (F^2x) as suggested by Rasul and Ali (1968).

Besides the above replacement textures, the presence of minor fractures, vein, vug and void was found to be more frequent and characteristic of these limestones. Their confinement to dolomite and the loosely compacted nature of dolomite crystals clearly suggest that dolomitization had been responsible for increasing the porosity of these limestones. Similar evidence was cited for increase in porosity through dolomitization by a number of authors including Murray (1960), Friedman (1965) and others.

Petrographic Discussions and Paragenesis:

The fine-grained and anhedral nature of the calcite indicates the fact that originally the limestones were fine-grained probably of micritic type (Folk's terminology 1959). The later processes of dolomitization and silicification, particularly, dolomitization, made the texture porphyrotopic. It is also apparent that the original fine-grained limestones were dolomitized incompletely or partially, because in the case of complete dolomitization, silica is not expected (see Carozzy, 1960, p.320). Moreover, the porphyrotopic texture of dolomite is also an indication of an incomplete dolomitization of limestone (see Friedman, 1965), Van Tuyl (1916).

The presence of silica in the vugs within dolomite and the replacement of some dolomite by jasperoid indicates that silicification followed dolomitization, which is true in many other similar cases as noted by Carozzy (1960, TABLE - II

Some important mineralogical characters and modal composition of silicified dolomitic limestones from lead-bearing horizons of Shishkhani-Chhanapani belt

S.No.	Section No.	Calcite %	Dolomite %	Quartz %	Crypto crystal silica jasperoid %	Opaques %	Misc. %	Description	Microscopic features
1	SK_1	69.0	8.3	2.1	20.2	0.41	-	Silicified dolomitic limestones	Jasperoid replaces calcite and dolomites. Vugs, veins, voids (all filled by jasperoid) are common.
2	SK_2	57.2	29.2	3.7	8.6	0.7	-	- do -	- do -
3	$SK_8 1$	59.39	17.8	3.1	10.7	0.73	.16 fibrous calcite	Silicified dolomitic limestone	Vugs, veins and voids more frequent (filled by jasperoid and fibrous calcite). Replacement textures also distinct.
4	$SK_8 2$	51.3	24.2	1.3	22.5	0.43	-	Silicified dolomitic limestone	Veins and voids normally walled by dolomite euhedra and filled by coarser jasperoid. Replacement textures also noted.
5	SK_{20}	16.8	5.3	-	77.2	0.7	-	Jasperoid	Highly silicified with few relict veins of dolomite and scattered patches of calcite.
6	SK_{21}	27.8	9.3	-	62.3	0.6	-	Jasperoid	Eating away phenomena well displayed. Ore intimately associated with jasperoid.
7	SKP_{54}	62.1	11.4	3.4	22.7	0.4	-	Silicified dolomitic limestone	Porphyrotopes of dolomite in fine calcite. Veins of quartz and galena common.
8	CP_4	56.3	14.1	0.9	28.1	0.6	-	- do -	- do -

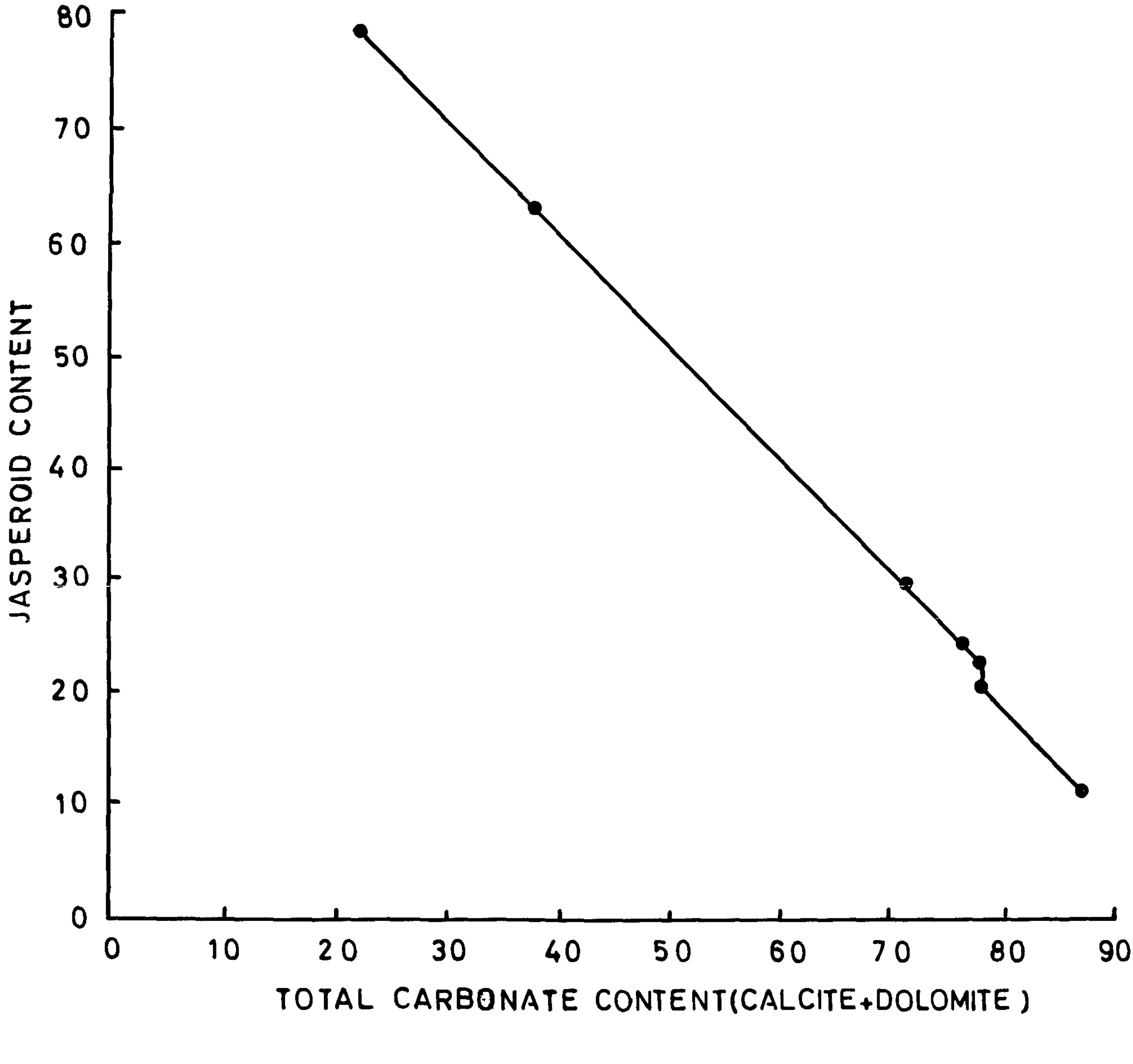

FIG. 8. VARIATION DIAGRAM OF CALCITE, DOLOMITE AND JASPEROID IN THE LEAD BEARING DOLOMITIC LIMESTONE, BAGESHWAR.

p. 320), Swett (1965, p. 935), Lovering (1949) and Lovering, T.G. (1969, personal communication). The presence of comb structure around galena and also of the veins of galena in jasperoid indicate that galena was deposited subsequent to jasperoid (cf. Grout, 1946).

These mutual relationships between the various stages and processes of replacement and lead ore deposition permit a probable sequence of events in mineral formation which in these limestones is remarkably consistant through out the region. The sequence of events is given as follows:

1. Dolomitization (incomplete)
2. Silicification
3. Lead mineralization

<u>Modal Composition of the Silicified Dolomitic Limestones</u>

The modal composition of the carbonate rocks (Table II) associated with lead deposits of Shish-khani and Chhanaapani belt clearly indicates that dolomitization and silicification have played an important part in altering the original nature of the fine-grained limestones. It is also evident that the silicification pattern in the mineralized zones is very much irregular. In some cases, the silicification is so intense that the percentage of jasperoid content goes upto 77. The variation diagram between calcite+dolomite and the jasperoid content shows a linear pattern (Fig. 8). The high content of calcite + dolomite is marked by a correspondingly low jasperoid content and vice versa. This feature further confirms the fact that jasperoid is formed at the expense of calcite and dolomite.

b) <u>Carbonate rocks with copper mineralisation</u>

In the mineralized belt of Bageshwar (Shishkhani-Chhanapani-Balaldev region) and also in Tamkhani region, the mineralisation of copper was recorded in the dolomites, talc-dolomite rocks and talc-schists. Some of the important petrographic characteristics of these rocks are described as follows:

a) The copper deposits occur in the dolomitized zones only.

b) The rocks are light coloured and composed mostly of coarse dolomite grains ranging in size from 6 mm to 2 or 3 cm.

c) The occurrence of talc in the dolomite is largely interstitial, often occupying fracture, cleavage and bedding partings.

Microscopically, the dolomites show all the characteristic properties of the mineral. In plane polarized light with partly closed iris diaphragm, the grains of dolomite are more distinct. Normally they are euhedral showing rhombic cleavage (Plate X, Fig. 3). They vary in colour from colourless, white to brown. The opaque minerals occupy only cleavage partings and fracture planes in the rocks (Plate X, Fig. 4). Twinning characteristic of dolomite is more frequent. The talc, which occurs along cleavages and fractures of dolomite is sometimes replaced by the copper and iron sulphides. Free silica is practically absent in the completely dolomitized zones in parts of the Balaldev copper deposits. It is important to note that the euhedral dolomite grains are loosely welded to one another leaving numerous intergranular spaces, some of which were later filled by sulphides and talc. In general, the textural and mineralogical symbol of codification of this kind of dolomite will be $M_{cu}(C^{3}10\ 80)$ with about 5 per cent talc (Rasul and Ali, 1968).

Some of the petrographic features of the partly altered carbonate rocks adjacent to the highly dolomitized zones are also interesting to note. Megascopically, these carbonate rocks are much more finer than the dolomites. In thin sections these carbonate rocks show a typical porphyrotopic texture

(Plate XI, Fig. 1). Well-developed rhombs of dolomite, many of which are slightly brownish and colourless, are scattered throughout the fine matrix. There is a distinct relation between the texture and dolomite content of these partly dolomitized carbonate rocks. The mineralogical variation (reflected by chemical variation discussed in the zoning, Chapter V) and the textural variation in carbonate rocks around the ore bodies appears to be harmonic. As one moves away from the ore body, the dolomite content decreases with decrease in their grain size. The porphyrotopes of dolomite (in the dolomitic limestones) adjacent to the completely dolomitized zones are bigger in size and greater in abundance than those of of the carbonate rocks away from the ore body (Plate XI, Fig. 2).

Interpretation and the Sequence of mineral Formation:

The dolomitized zones are composed of euhedral, coarse-grained, light coloured dolomite which envelope the ore stringers. All the above features are considered to be the characteristic of hydrothermal dolomites (see Hewett, 1928), Lovering (1949), Schwartz (1959) and others.

The presence of numerous intergranular spaces in the dolomites and their poorly welded nature clearly indicate that the dolomitization was responsible for the increase in the porosity of these carbonate rocks. Such textures, according to Hewett (1928), Tarr (1936), Murray (1960), Friedman (1965) and others, are indicative of the increase in porosity through dolomitization.

In the adjoining transitional or less affected zones the porphyrotopic nature of the dolomitic limestone indicates an incomplete dolomitization of the original fine-grained limestones (see Van Tuyl, 1916; Ohle, 1951;

Friedman, 1965). The occasional presence of irregular patches of dolomite in the limestone is also a criterion of incomplete replacement of calcite by dolomite (see Friedman and Sanders, 1967, p. 295). Harmonic variation in the Ca/Mg ratio (in other words dolomite content) around the ore bodies seems to have been controlled largely by the temperature of the hydrothermal solution responsible for copper mineralization.

The copper ores are also invariably associated with the talc-dolomite rock and talc schist. The presence of talc in the copper bearing rocks may be regarded as a criterion of hydrothermal metamorphism of the rock under low temperature conditions (see Bateman, 1959, p. 296). The replacement of talc-schist along its cleavage partings by copper sulphides indicates that the formation of talc preceeded the deposition of sulphides. The occurrence of talc in fractures and open spaces within dolomite is another evidence in support of formation of talc after dolomitization of the carbonates as a result of hydrothermal alteration. Actually, this subject of epigenetic replacement is related to hydrothermal activity and hence it is being discussed at some length in the chapter on wall rock alteration.

The probable sequence of hydrothermal events beginning with the dolomitization of the limestones may therefore, be presented as follows:

1. Dolomitization of the limestone.
2. Formation of talc in dolomites.
3. Deposition of copper-iron sulphides.

<u>Origin of dolomite</u>: The origin of dolomite has long been a subject of great speculation and controversy in sedimentary geology (see Murray and Pray, 1965).

According to Leighton and Pendexter (1962, p. 57-58), Bissel and Chilingar (1967, pp.112-113), the dolomites may either be primary or secondary in origin. The primary dolomites are those, according to Rodgers (1954, p.232), which are formed by direct precipitation from the sea water.

Some of the characteristic features of primary dolomites as suggested by Leighton and Pendexter (1962, p. 58), and Bissel and Chilingar (1967, p. 112) are summarized below to facilitate a comparison between the dolomites of primary and secondary origin.

1. Generally fine-grained, aphanitic to finely crystalline with uniform texture.
2. Laminated or interlayered.
3. Commonly associated with anhydrite, gypsum or red-shale or siltstone.
4. Relict limestone textures are absent.

The following observations were made in the case of dolomites of Bageshwar:

1. Dolomites are invariably coarsely crystalline and euhedral in completely dolomitized zones. The porphyrotopic texture is common in zones adjacent to the ore bodies.
2. They have no lamination or interlayering.
3. Also, they are not associated with anhydrite, gypsum or red shales and siltstone. The association of dolomite and talc is common only in the dolomitized zones.
4. Relict textures in the limestone are common only in the incompletely dolomitized carbonate rocks.

All the above mentioned features, thus, suggest that the dolomites associated with the copper deposits of Bageshwar may not be of primary origin. A secondary origin is, therefore, envisaged here for the dolomites whose features are characteristic of dolomitized rocks (see Bissel and Chilingar 1967, p. 112).

Some more interesting observations were made by Friedman and Sanders (1967) on the origin of dolomites. The dolomites, according to them, may be either (1) syngenetic, (2) detrital, (3) diagenetic or (4) epigenetic.

The textures, structures and mineral assemblages as described by Friedman and Sanders (1967, p. 268, and 308-309) for syngenetic dolomites are the same as that of the primary dolomites of Leighton and Pendexter (1962, p. 57-58) and Bissel and Chilingar (1967, p.112). Hence the view of syngenetic origin for the dolomites in question may easily be discarded. A detrital origin for these dolomites is also not possible because of the complete absence of any detrital texture in the rocks. Some of the salient features of detrital dolomites as observed by Lindholm (1969, pp.1035-1038) are given below:

1. Dolomite and detrital quartz are present together. The high dolomite content is marked by high values of detrital quartz.
2. The grain size of the detrital quartz and the dolomite is approximately the same.

The above two evidence may be taken as negative evidence of a non-clastic or non-detrital origin of the dolomites under review because, (a) there is no such association of dolomite and the detrital quartz. Moreover, it is also found that the high dolomite content (as in the case of completely dolomitized zones) is marked by complete absence of free quartz, (b) In the silicified zones, however, silica and dolomite occur together. In such cases, coarsely textured dolomite shows evidence of its replacement by fine silica. The grain size of the two minerals is also not comparable.

Now, the two possibilities are left to account for the origin of the dolomites. They can either be epigenetic or diagenetic. As pointed out by Friedman and Sanders (1967, p.328) that the diagenetic dolomites are normally related to "the surfaces of stratigraphic discontinuities (or unconformities)" and in many cases are similar to syngenetic dolomites. In the area under review, the occurrence of dolomites has no such relationship to the surfaces of stratigraphic discontinuities. Moreover, their coarsely crystalline nature does not agree much with the diagenetic dolomites which were reported to be fine-grained by Friedman and Sanders. Therefore, these dolomites could only be formed by epigenetic processes. Following are the evidence in support of an epigenetic origin for the dolomites of Bageshwar:

a) The dolomites are genetically related to the copper deposits. Friedman and Sanders (1967, p. 332) suggested such a relation as one of the general characteristics of epigenetic dolomites.

b) More fracturing and greater porosity and permeability of the coarse grained copper bearing dolomites than the less altered barren carbonate rocks is another characteristic feature of epigenetic dolomites. Similar view for the origin of epigenetic dolomites were expressed by Howett(1928), Lovering (1949), Schwartz (1959, p.167) and Friedman and Sanders (1967, p.332-333).

c) A harmonic variation in texture and dolomite content of the carbonate rocks around the ore bodies perhaps indicates "the diminishing activity of a powerful hydrothermal source" (see Lovering, 1949, p.3) which culminated with the deposition of sulphides in this region. And probably this activity, at an earlier period, not only led to the formation of epigenetic dolomite but also to the porphyrotopic dolomitic limestone which is associated with the dolomites in the vicinity of the ore deposits. It may, therefore, be finally suggested that the dolomites associated with the copper deposits of Bageshwar are secondary and formed epigenetically.

2. Barren carbonate rocks

About sixty thin sections of the barren carbonate rocks containing no trace of Cu-Pb-minerals, were studied in order to compare them with the metal-bearing portions of the same rock. Folk's (1959) and Friedman's (1965) classifications were applied in these barren carbonate rocks. The classification suggested by Rasul and Ali (1968) has also been used wherever applicable. An attempt has also been made to discuss briefly the environment of the carbonate deposition.

The following types of the barren carbonate rocks have been recognized:

Type 1 Calcareous phyllites
Type 2 Fine-grained and silicified limestones
Type 3 Stromatolitic limestones

Type 1: Calcareous phyllites

The calcareous phyllites are generally very finely crystalline and on weathering, the rocks become soft and friable. Due to the occasional presence of some red iron oxides, some of the calcareous phyllites look reddish and pinkish in colour. From several vugs in these rocks near Raikheli, beautiful rock crystals were collected. The phyllites have the characteristic silky sheen and show shistosity but in a poor state of development (Plate XI, Fig.3). Bedding traces are distinct and follow more or less the foliation direction.

Thin sections of the rocks show the presence mainly of calcite, quartz, sericite, a few opaques and some clay minerals.

Calcite : Calcite is the most abundant constituent of these calcareous rocks. It is light brown in colour. The grains of calcite are oriented parallel to the foliation of the enclosing rock. In many cases calcite occurs in the form of fibres which are often bent and dislocated. There are also some cross fibres of calcite in vugs and veins (Plate XI, Fig. 4). The calcite content of these calcareous phyllites ranges from 40 to 60 per cent as counted in 10 thin sections.

Silica : Two varieties of silica may easily be recognised. The coarse-grained one may be the primary quartz, i.e., one of the original constituents of the rock. It is rather free from any inclusion and interlocked with calcite. It also shows preferred orientation with respect to the rock cleavage direction. The other variety of silica is the fine chert.

Sericite : Sericite is the most common accessary constituent in these phyllites. Finely crystalline and fibrous aggregates of sericite are present more frequently in the less calcareous portions of the rock.

Opaques : Euhedral and sometimes deformed cubes of pyrite may be identified in the hand specimens of the red and pink calcareous phyllites. In thin sections, however, pyrite, which is mostly oxidised, is indicated by the presence of deep red and yellowish limonite. A small quantity of elongated, platy and sometimes rod-like opaque iron oxide, showing preferred orientation with the associated minerals is present in the ferruginous variety of calcareous phyllites (Plate XI, Fig.3).

Clays : Some thin dark bands were recognised as carbonaceous clays. There are some other white clays associated with the more argillaceous portions of the rock.

Grade of metamorphism : Judging from the textural characters of the minerals and their assemblages, it may be concluded that these phyllites are the products of regional metamorphism of the lowest grade of calcareous shales

TABLE - III

Chemical Analysis of Barren Carbonate Rocks

Sample No.	SiO_2	R_2O_3	CaO	MgO	$CaCO_3$	$MgCO_3$	CaO/MgO	Total
1	0.36	1.10	53.76	1.60	96.00	3.36	38.60	100.82
2	24.60	3.74	37.52	1.80	67.00	3.78	20.8	99.12
3	5.76	1.56	50.40	1.20	90.00	2.52	42.00	99.84

(Analyst: Mohd. Zafar)

Sample No. 1 Limestone, from Kaphauli, $1^1/2$ miles south of Bageshwar.

Sample No. 2 Limestone, from Chhana, 3 miles NNW of Bageshwar.

Sample No. 3 Limestone, from Belauna Sera, 1 mile south of Bageshwar.

having a little of silica.

Type 2 : Fine-grained limestones

The petrography of the fine-grained limestones is a tedious task. Under the vague term fine-grained limestones, a number of limestone subtypes have been included. The megascopically identified fine-grained limestones are further subdivided into some two varieties as follows:

Variety 'A' : This variety of limestone is generally very finely crystalline and composed mainly of calcite and quartz, including some detrital quartz. Calcite shows a faint brownish colour in thin sections and generally it is fine-grained equidimensional (Plate XII, Figs. 1,2). The calcite grains are usually xenotopic showing mosaic texture under high magnifications.

Due to recrystallization some of the quartz shows interlocking texture with calcite. A few detrital or terrigenous quartz may also be seen in a few thin sections. Allochems are practically absent or, even if present, might have been obliterated due to the recrystallisation.

Judging from the composition and texture, these limestones are classified as "Microsparites" (i.e., R III m) in Folk's (1959, p.32) classification. Rasul and Ali's (1968) code for such carbonate rock will be B(F^2x 900). An average CaO/MgO ratio value of three barren carbonate rocks was determined as 33.70 (see Table III).

Variety 'B' : Silicified limestones - Megascopically, these carbonate rocks are fine-grained and light grey in colour. The rock is composed mainly of fine chert with a few unreplaced grains of calcite in the form of inclusions or small patches. Chert does not occur in veins in these barren silicified limestones. There is no evidence of dolomitization prior to silicification. The fine-grained nature of chert indicates a rapid rate of replacement

(Folk and Waviers, 1954) probably within the diagenetic sequence.

An attempt is made in the following table to compare the silicification patterns of the mineralized and barren carbonate rocks:

TABLE - IV

The lead-bearing silicified carbonate rocks	The barren silicified carbonate rocks
1. The formation of jasperoid associated with lead ores normally follows dolomitization.	1. The silicification in these rocks does not show any evidence of dolomitization prior to silicification. A few exceptional cases are also present.
2. Besides the replacement of carbonate minerals by jasperoid, the silicification in these rocks is also indicated by the presence of thin veins, veinlets, fractures and vugs filled by silica.	2. This cryptocrystalline silica is practically free from veins, vugs and voids, but is often laminated.
3. The variation in grain size of the jasperoid is an important feature. In a few vugs, the silica grains are euhedral to sub-hedral with a size upto 0.5 to 0.75 mm in diameter. The grain size of the silica enclosed in masses of galena ranges upto 4 mm in diameter. The jasperoid, which replaces the carbonate minerals, is much more finer than the silica which is found in vugs and open spaces.	3. Texturally, this silica is very finely crystalline to sphaerocrystalline. No distinct variation in gram size in a single thin section could be seen.

Type 3 : <u>Stromatolitic limestone</u>:

The stromatolitic limestones are composed mainly of pink and white concavo-convex laminae (Plate I, Fig. 4). Several thin sections of these limestones were studied and a polished specimen was also studied under reflected light.

Under microscope, no recognizable structure (other than megascopically visible laminations) may be seen. Thin sections do not show any sign of algal structure. These rocks are composed mainly of recrystallized calcite with a few patches of scattered dolomite. Reddish and yellowish coating is probably due to some ferruginous material present in the pink laminae of the collenia.

Probable environment of carbonate sedimentation

In all probability, the carbonate rocks of the calc zone of Bageshwar were originally deposited as the textural type "Micrites". Due to the low grade of regional metamorphism which may correspond to the 'Clastic mica zone' (of Harker, 1939, p.209), the recrystallization of the original micritic carbonate rock produced 'microsparite'.

According to Folk (op.cit., p.12), the micrites are formed by "a rapid rate of precipitation of micro-crystalline ooze together with lack of persistant strong currents". He (p.26) further suggests that "these rocks could accumulate either in shallow, protected shelves or lagoons as in Bahamas or in calm deep waters". Here for the calc-zone of Bageshwar, a protected shallow lagoon environment is very much suggestive, because of the association of the algal stromatolites with the carbonate rocks.

The presence of algal stromatolites further throws some light on the environment of deposition of the carbonate sediments. Cloud (1942) states that the maximum depth upto which the stromatolites could have been formed is 30 meters in the saline waters and 10 meters in fresh waters, i.e., the depth is shallow enough to be penetrated by the sun's rays.

Thus, it appears that once a protracted marine environment, shallow and clear enough for sun's rays to penetrate and also warmth favoured a prolific algal growth in the present area. The environment of the deposition of micritic limestones and the algal limestones in general, are thus, very much similar.

B. Bageshwar Quartzites

A brief microscopic description of the various petrographic types of the Bageshwar quartzites is given herewith. The nature of the original sediments and their subsequent metamorphism has also been discussed in brief.

Megascopically as well as microscopically, the Bageshwar quartzites may be divided into the following two major types:

1. Metamorphosed ortho-quartzites.
2. Graphite-quartz-schist.

1. Metamorphosed orthoquartzite - The bulk of the Bageshwar quartzite group may be designated as metamorphosed orthoquartzites. (Pettijohn's terminology, 1957, p.296). Megascopically, these rocks are fine to coarse grained and pink, yellow or white in colour. Sedimentary structures like current bedding, ripple marks, etc., may often be seen in these quartzites.

Microscopic features: Under the microscope, however, the metamorphic nature of these quartzitic rocks is very well marked. Mineralogically, these rocks are composed mainly of the porphyroblasts of quartz in a matrix of chert, sericite and dusty iron oxides (Plate XII, Fig.3). The presence of minor heavy minerals like well-rounded tourmaline and zircon has also been recorded.

The size of the quartz grains varies from .3 mm to 1.8 mm in diameter. On the basis of their size quartz grains, two types of quartzite may be recognised, (1) fine-grained and (2) coarse-grained orthoquartzite. The degree of sorting, even though modified by metamorphism, appears to be good (Plate XII, Fig.4).

Quartz: Quartz comprises approximately 97 to 99 per cent of the rock while heavy minerals and some ferruginous material, now much replaced by silica, make up the rest. Colourless, subrounded to sub-angular, quartz have some inclusions of tourmaline, zircon and iron dust.

__Chert__ : This cryptocrystalline variety of silica is the most common matrix in these quartzites. The chert content of these rocks varies from 5 to 25 or sometimes 30 per cent and about 90 per cent of the material contributing to the matrix is made up of chert. Chert shows well defined mosaic texture.

__Sericite__ : Colourless, minute specks of sericite, showing upper first order polarization colours, occurs in the cherty matrix and around the porphyroblasts of deformed quartz grains. About 5 to 10 per cent of the fine matrix is composed of sericite flakes.

__Textural features__

Almost all the quartz grains in thin sections invariably display undulose extinction and some fracturing. Boehm striation is very common in medium and coarse quartz grains. In the majority of cases, the original detrital outlines of the quartz grains were obliterated by marginal granulation and recrystallization. In most of the thin sections the elongated and elliptical quartz grains have preferred orientation (Plate XIII, Fig. 1). At places, the quartz grains are enclosed by bent sericite. There are also some pencil-like crystals of iron-oxides which have the same preferred orientation as that of the quartz and sericite. Chert has a mosaic texture and at places bands of chert are arranged parallel to the larger quartz grains. In certain cases, these quartzites show a mosaic texture (Plate XIII, Fig.2). Some equigranular and medium grained orthoquartzites show complete absence of any cementing material. In such cases, interlocking or mosaic texture is well-defined. In general the texture of these rocks varies from blastopsammitic to mosaic.

Petrographic discussion, the nature of original sediments and the grade of metamorphism

The relict texture, blastopsammatic texture, the remnants of rounded or subrounded quartz grains and the high silica content of the rocks indicate that these originally clastic sedimentary rocks were orthoquartzitic (see Pettijohn, p.296, 1957) in composition and texture.

Metamorphism has largely obliterated the original nature of the sediments as indicated by the following observed facts:

1. The presence of undulose extinction in almost all the quartz porphyroblasts.
2. The presence of Boehm striations in quartz is the most common effect of metamorphism.
3. Elongation of quartz grains into lenticular form and their preferred orientation together with the development of sericite is another evidence of metamorphism.
4. The marginal granulation of quartz porphyroblasts is a common cataclastic metamorphic effect on the originally rounded or subrounded quartz.
5. The inter-locking nature of the fine chert as well as some porpyroblasts is another evidence of its metasedimentary nature.

The grade of the regional metamorphism may be of the order of clastic mica zone of Harker (1939, p.209).

2. Graphite-quartz-schist

Thin lenticular bands of graphite in the quartz-schist have been recorded at a number of places in the area. A good exposure of this rock was located about 1 mile NW of Bageshwar along a creek. This variety of quartzite is easily recognised by the shining brownish-black colour and the greasy feel of the mineral graphite. It shows poorly developed schistosity defined by the parallel arrangement of minute sericite and graphite flakes.

Under the microscope, quartz may be seen surrounded by graphite (Plate XIII, Fig. 3). The textural arrangement of sericite and graphite may be said to be lepidoblastic. Under reflected light graphite may also be recognised by its pleochroic tendency.

C. Altered Basic Sills

Altered basic sills represented by the chlorite-schists and low grade epidiorites constitute a prominent intrusive rocks in the Bageshwar area and especially associated with the Bageshwar quartzites. These rocks are in fact metamorphosed representatives of some basic igneous rocks. A marked variation in the composition, texture and physical nature may well be observed even in the field. The unweathered basic rocks that are encountered in the Mandalsera, Joshigaon regions are dark green with yellowish shade in colour. The alteration and weathering of the basic rocks at a number of localities is marked by a yellowish and reddish colour.

A petro-mineralogic account of the basic sill is given as follows: Actinolitic hornblende (uralite), albite, epidote, chlorite, sphene, magnetite, biotite (with or without calcite and quartz) are present in the epidiorite.

These basic rocks of epidioritic composition are more common. The important mineral constituents and their textural relationships are described as follows:

Hornblende : Hornblende occurs in prismatic crystals, sometimes, fibrous (actinolitic) and streaky in appearance (Plate XIII, Fig. 4). At places, euhedral six-sided hornblende crystals with two sets of cleavages may also be seen. Elongated four sided grains usually show one set of prismatic cleavage. Plates of hornblende (pseudomorph after augite) are also common in some thin sections. The hornblende is yellowish green in colour with a marked pleochroism, displays high order polarization colours. Extinction angle in four-sided hornblende crystals varies between 12° to 21°.

__Albite__ : Albite is the only felspar occurring in the rock. Both cloudy and fresh albites are present, Carlsbad twinning is more frequent than the lamellar twinning. The intimate association of albite and the saussurite group of minerals is an important feature noted in all the thin sections (Plate XIV, Fig. 1). The saussurite group of minerals under high magnification, indicate the presence of epidote, zoisite, etc. The extinction angle of the twinned grains of albite varies between 10° to 12°.

__Epidote__ : Epidote occurs as colourless to light yellowish green. It is noted mostly in the form of minute grains or clusters in and around the albite grains. Lower order polarization colours, high relief and parallel extinction in short prismatic crystals are its characteristic features. Inclusions of epidote in hornblende may also be seen.

__Chlorite__ : Chlorite is streaky and associated with hornblende, albite and iron oxide. It is pale green to light green in colour, feebly pleochroic and shows first order grey polarization colours.

__Biotite__ : Biotite gives light brown to dark brown Pleochroic colours and straight extinction. It occurs in close association with hornblende.

__Calcite__ : Calcite occurs associated with albite, epidote and quartz. It is colourless in thin sections and recognised by its well-defined rhombohedral cleavage, twinning, polarizing colours and twinkling. There are some inclusions of epidote in calcite.

Sphene : Sphene is associated with hornblende and magnetite. Brownish in colour, skeletal in form with a small core of opaque magnetite, sphene very characteristically displays very high relief and brownish pink polarization colour (Plate XIV, Fig.2).

Magnetite : Under the microscope octahedral crystals of opaque magnetite may well be recognised in the core of sphene and elsewhere in association with hornblende.

Quartz : A little of free silica in the form of quartz occurs in association with calcite.

Textural features : In general, the texture of these metamorphosed basic rocks is granoblastic. Poorly defined schistosity has also been marked in a few thin sections and hand specimens. A careful observation, however, indicates a very well defined blastophitic texture. Here, the aggregates of hornblende grains enclose laths of fresh albite with inclusions of epidote, zoisite,etc.

Petrographic discussions and the petrogenesis

The mineral assemblage, textures and microstructures of these basic rocks of Bageshwar area show a remarkable resemblance with low grade epidiorites as described by Wiseman (1934).

From the petrographic studies, it is also evident that the alteration of augite to hornblende (in nearly all cases) is complete. The complete absence of pyroxenes thus pose a problem particularly as regards the genesis of hornblende. The following features, however, suggest that hornblende was derived from the pyroxene (probably augite).

1) The tabular form of augite preserved in hornblende.
2) The preservation of the original ophitic texture (now represented by the albite laths enclosed in hornblende).
3) The fibrous (actinolitic) hornblende variety indicates the replacement of pyroxene by hornblende.

About the nature of metamorphism in the basic rocks it is evident that saussuritization and uralitization were the two important simultaneous processes involved. The process of saussuritization involves the breaking down of plagioclase felspars with the separation of Na and Ca into different products. The sodic component separates out as fresh albite, while the calcium occurs chiefly as a component of epidote, zoisite, etc. Uralitization of the pyroxenes, which is accompanied by saussuritization produced the fibrous (actinolitic) hornblende, etc. (see Heinrich 1956, p.257, and Harker 1939, p.174).

The textural and mineralogical assemblages suggest that originally the sills were diabasic in composition.

D. The Crystalline Series

This group comprises rocks having a wide range of mineral composition and extreme variation in texture and structure. Detailed microscopic examination has not been undertaken in this case. These rocks also exhibit variation in the grade of metamorphism. The following rock types have been recognised under the microscope:

I. Cataclasites
   a) Mylonites
   b) Phyllonites
   c) Mylonitic augen-gneiss

II. Quartzites

I. Cataclasites

a) Mylonites - Highly crushed and sheared rocks, exposed along the main thrust have been classified as mylonites. Megascopically, they are thin bedded, frequently showing minor folding, brownish green rocks with numerous veins of quartz.

Under the microscope, the grain size is extremely fine with a few lenses of slightly coarser sericitized felspar and fractured quartz.

b) Phyllonites - These are the fine-grained phyllitic rocks, whose fine texture results from the crushing of coarser grains. Highly sericitized felspar and quartz grains have been bróken into small pieces and the smaller bróken pieces of quartz sometimes exhibit mortar structure. Sericite, chlorite, quartz are the major constituents of these phyllitic rocks. Bent cleavages, microfolds and microfaults have been observed in the flaky minerals like chlorite and sericite.

c) Mylonitic augen gneiss - Quartzose felspathic mylonitic augen gneisses have been encountered in the crystalline zone, about a mile NW of Kathathbara. The augen structure is recognisable even megascopically. The rock is composed mainly of the augens of felspar and quartz with fine chlorite, muscovite, epidote, sericite, iron oxide, etc.

Quartz displays cataclastic textures like mortar structure, boehm striation and granulation boundaries. The sericitization of plagioclase felspar is sometimes so intense that it is difficult to distinguish the particular variety of the plagioclase felspar. Development of muscovite laths around the borders of the sericitized felspar grains is another feature to mark.

Crumpled and bent chlorite and muscovite enclose lenticular and eye-shaped grains of quartz and sericitized plagioclase felspar, displaying a very well-defined augen structures (Plate XIV, Fig. 3).

II. Quartzites

The quartzites of the crystalline zone exhibit a well-defined mosaic texture under the microscope. Quartz is the most important component of the rock ranging from 75 to 85 per cent by volume. Quartz in most cases, shows cataclastic effects like mortar structure, fracturing and granulation of its grain boundaries.

Muscovite is next to quartz in abundance, showing bent cleavages. Biotite and muscovite occur in interstitial boundaries of quartz grains. (Plate XIV, Fig. 4). Heavy minerals include zircon, epidote, tourmaline and some opaque iron oxides.

Chapter - V

WALL ROCK ALTERATION, ORE ZONING AND GUIDE TO ORE DEPOSITION

A. WALL ROCK ALTERATION

1. General Statement

In epigenetic ore deposits hydrothermal alteration of the country rocks, either associated with the ores or forming the wall rocks of the mineralized veins, is a common feature. As a guide to ore, the detection of the hydrothermal alteration within and around the eprgenetic ore deposits is of great significance.

The importance of hydrothermal alteration, according to Lindgren (1896) is: "The study of changes and alteration which the rocks adjoining fissures have undergone is a subject of the highest importance, for in this way a closer insight into the genetic processes of the veins may be obtained".

Schwartz (1955, p.300) has emphasised the importance of hydrothermal alteration as follows: "Hydrothermal alteration because it is commonly pervasive in the vicinity of ore deposits furnishes a valuable guide in the exploration for new ore bodies". According to Schwartz (1959), the hydrothermal alteration is extensively variable, depending upon: (i) the composition of the original minerals and rocks, (ii) composition of the solution, (iii) temperature, (iv) pressure and (v) the time involved.

It is generally assumed that the hydrothermal alteration associated with ore deposits is contemporaneous with ore deposition. The different mineralogical zones in the ore bodies and the surrounding country rock are just like the reaction rims representing the diminishing activity of the powerful solutions that deposited the ore (Lovering, 1949, p.3 and Lindgren, 1933, p.185). Different periods of hydrothermal activity, separated by different time intervals are represented by various alteration zones (Lovering 1949, p.3).

Common alteration minerals characteristic of various types of mineralization, compiled after Bateman (1959), McKinstry (1948), Park Jr., MacDiarmid (1964) and Schwartz (1955, 1959) are summarised in table V.

TABLE - V

Conditions	Wall rock	Processes involved	Some alteration products
Telethermal	Limestone	Dolomitization	Coarser dolomite
		Silicification	Fine-cryptocrystalline silica, jasperoid. (Park Jr. & MacDiarmid, 1964, p.331).
Epithermal	Limestone	Carbonization	Calcite, dolomite, rhodochrosite and also talc.
		Silicification	Jasperoid.
	Potassium bearing silicate rocks	Alunitization	Alunite (Schwartz, 1955, p.311).
	Intermediate to mafic volcanics	Prophylitization	Prophylite, aggregate of secondary chlorite, epidote, sericite, etc. (Park Jr., MacDiarmid, 1964, p.313).
Mesothermal	Potassium bearing silicate rocks	Alunitization	Alunite (Schwartz, 1955, p.311).
	Argillaceous material	Sericitization and bleaching	Sericite (Anderson, 1949, p.170; Park Jr. & MacDiarmid 1964, p.296).

(contd.)

Table -V (Contd.)

Hypothermal	Granitic rocks	Schists, Lavas	Greisen: topaz, white mica, tourmaline; pyroxenes, amphiboles
Xenothermal		Ranges from tourmalinization to kaolinization and alunitization	Tourmaline, kaolin, Alunite, etc. (Park, F.Jr. & MacDiarmid 1964, p.347).

2. A brief review of the concept of wall rock alteration

Wall rock alteration has long been considered as a valuable tool in mineral exploration because the altered zones are more widespread than the ore bodies. In a casual study it may be difficult to trace back to the first recognition of a relationship between hydrothermal alteration and epigenetic mineral deposits.

Schwartz (1959) has given a long list of the previous workers in this field of economic geology. He states that Agricola, even in 1546 had some realization that ores were related to heated waters and vapors and Darwin in 1846 had recognized the relation between metamorphism and metallic veins.

About the paragenesis of ore and alteration, Emmons (1896, p.468) says, "This supposes a prolonged alteration and decomposition of the rocks along the water channels before the actual deposition of metallic minerals". Further, he reported a close association of Kaolin and Pyrite crystals in highly altered material within the area of ore deposition and believed that the formation of kaolin due to alteration was a part of the ore forming process.

Soon after the recognition of the nature of epigenetic ore deposits, an intensive study of the wall rock alteration began particularly in the European and American continents. Waldemar Lindgren may probably be considered as one who has contributed most to this concept of ore-genesis. Lindgren (1894) for the first time described in detail the petrography and chemical nature of the altered and unaltered rocks associated with the gold-silver veins of Ophir, California. This type of study is perhaps still valid.

In 1896, Lindgren (p.91), described another type of alteration associated with ore-deposits, viz., the common hydro-metamorphism and the minerals formed under this common hydro-metamorphism. are: chlorite, serpentine, hornblende, epidote, muscovite, scapolite, zeolite, etc. Bateman (1959, p.296) considered the mineral talc to be a product of hydrothermal metamorphism.

Spurr (1908, see Schwartz, 1955, p.309) described the nature of wall rock alteration especially, the process of silicification and named the cryptocrystalline quartz (of replacement origin) as jasperoid.

Ransome (1907) described the association of alunite with gold in the gold field district of Nevada. In 1905, Skeats published a paper on the chemical and mineralogical evidence supporting hydrothermal origin of dolomites of southern Tyrot, Italy (see Hewett, 1928, p.842). Bain (1924), while describing the replacement deposits of magnesite observed that there was a zone of dolomite between limestone and magnesite. Hewett (1928), in his classic paper reviewed the literature on dolomitization and ore deposition. The most important observations made by him are that the hydrothermally formed dolomites are: (1) coarse-grained in texture and (2) light coloured in nature. His results are still valid and these have been applied with success by many authors including Lovering (1949), Schwartz (1959) and Ohle (1951) in their recent papers. Since 1930, a voluminous literature has been added from all parts of the world. Some of the noted workers who made valuable contributions in this regard are: Hewett (1931), Lovering (1941, 1949), Ohle (1951), Sales and Meyer (1948, 1950), Kerr (1950,1951), Stringham (1952, 1964) and Schwartz (1947, 1955, 1959).

Lovering (1949) in his excellent monograph has recognized five stages of hydrothermal alterations in the East Tintic district, Utah. According to his interpretations each of the five stages are separated from one another by appreciable time intervals representing a period of hydrothermal activity. Sales and Meyer (1948, 1950) also made an excellent study of the Butte copper deposit, Montana. Their inference is that in a reactive wall rock, a hydrothermal solution at a particular distance from its magmatic source would cause a specific type of alteration and that the same solution in the same country rock at a different distance would cause a different type of alteration.

Ohle (1951) studied the permeability of hydrothermally altered carbonate rocks in Tennessee, U.S.A./and concludes that the permeability increases through dolomitization.

Schwartz (1955, 1959) reviewed the literature available on hydrothermal alteration and discussed the problems of zoning, the origin of hydrothermal solution, etc. Gawad and Kerr (1959) noted incipient silicification in the dolomitized zones of Basal Chilne deposits. The source of silica, as they say, is the hydrothermal solution. Lovering, T.G. (1962a, 1962b, 1966,

1968) studied the origin of jasperoid in limestone and other genetic problems of jasperoid associated with sulphide deposits.

Burnham (1962) grouped the hydrothermally altered rocks into two principal facies viz., the argillic and phyllic facies. He further sub-divided the argillic facies into propylitic, montmorillonitic and kaolinitic types; and the phyllic facies into muscovitic and biotitic types. Recently, Maxham, Foote and Bunker (1965), determined by chemical analysis the uranium, thorium and potassium contents of hydrothermally altered rocks in the vicinity of several copper and copper-lead-zinc deposits in Arizona.

In India, Das Gupta et al. (1963), Das Gupta (1963), Ashoke Mukerjee (1964), Sen Gupta (1963), Ziauddin and Sharma (1968) have contributed a number of good papers on the problem of the alteration of wall rocks associated with the copper deposits of Singhbhum (Bihar), Khetri (Rajasthan), Agnigundala (Andhra Pradesh), Kolar Gold Fields (Mysore) and the lead-zinc deposits of Zawar (Rajasthan). Ziauddin (1965, personal communication) has pointed out that the wall rock alteration in the Agnigundala copper deposits, Andhra Pradesh, is marked by dolomitization and silicification. Among other alteration products, he recorded sericite, chlorite and tourmaline.

3. Previous investigations

None of the workers, who had previously investigated the base metal deposits of Bageshwar, made any serious attempt to study the nature of wall rocks of the deposits.

Subramanyam and Jain (1961, 1964) reported the occurrence of copper and lead ores in the dolomitic limestones of Garhwal Series. Nautiyal (1962) very rightly believes that the silicification and the formation of talc is related to the hydrothermal activity associated with the copper deposits of Almora and Pithoragarh districts of Uttar Pradesh. Rasul and Ali (1968) proposed a codification of the hydrothermally altered carbonate rocks associated with some of the copper and lead deposits of Almora district, Uttar Pradesh.

4. Present investigation

Alteration of wall rock is one of the important observations made by the author while investigating the copper and lead mineralization at Bageshwar. The limestone is the chief wall rock involved in this alteration. The dominant processes involved in the hydrothermal alteration are: dolomitization, silicification and formation of talc.

A large number of thin sections of rocks from both altered and unaltered portions of the country rock around the deposits of copper and lead were examined. The rocks show a wide range in composition and texture.

A detailed study of the rock-forming minerals and their field relations shows at least three main types of hydrothermal alteration with minor variations. All the three types refer to the ore-bearing rocks and not to the marginal zones. The more or less distinct types with examples of localities are as follows:

a) Dolomite, talc-dolomite rock - Hydrothermal alteration involving formation of dolomite and talc-dolomite rocks are associated with almost all the known copper deposits of Bageshwar. The localities are: Balaldev ridge (southern, eastern and northern edges), Ghirauli, Tamkhani, etc.

b) Talc-schist - Talc-schist was encountered about 200 yards northwest of the northern edge of Balaldev ridge. Mineralization of copper occurs along the foliation planes of talc-schist.

c) <u>Silicified dolomitic limestone</u> - All the lead mineralization in this region is confined to the silicified dolomitic limestone, which occurs on the north-northeast and the northeast of the Balaldev ridge, about 4 furlongs away, and also in the south and SW of the same ridge. The localities are Pur Shishkhani, Chhanapani, Short and south of Balaldev ridge.

It should be emphasised here that the above localities and the corresponding products of alterations are not simple examples of one type of alteration. Considerable overlapping has been observed. The detailed petrographic studies revealed that some localities show several kinds of alteration though perhaps, one kind overshadows the other as recorded at Pur Shishkhani and Chhanapani where both dolomitization and silicification are intimately associated with the lead ores. The Balaldev copper deposits, for example is also associated with the two processes, viz., dolomitization and the formation of talc. Each deposit thus can be classified as having two types of alterations.

6. <u>Effects of hydrothermal activity</u>

Study of the petrography, paragenesis and field relations of the altered rocks shows at least two distinct phases of hydrothermal activity. Again, each phase is characteristic of two types of alterations. The paragenetic sequence of the two phases of hydrothermal activity, the types of alterations are worked out as follows:

First or earlier phase of hydrothermal activity:

Alteration and mineralization	T i m e
Dolomitization	
Formation of talc	
Cu-Fe mineralization	

Second or late phase of hydrothermal activity:

Alteration and mineralization	T i m e
Dolomitization	
Silicification	
Lead mineralization	

The above mentioned phases of hydrothermal activity, with their respective paragenesis of alteration and ore deposition are very significant in the Shishkhani-Chhamapani-Balaldev belt of copper and lead.

a) First phase:-

(1) Dolomitization and formation of talc - The formation of secondary dolomite in the altered limestones is well seen in parts of Balaldev ridge, in Ghirauli and Tamkhani villages in the Bageshwar area. In all the above localities the highly dolomitized zones are formed around the copper deposits. At Balaldev, the southern, eastern and northern edges of the ridge are distinctly dolomitized. The dolomitized limestones are composed of extremely coarsely crystalline dolomite which is idiotopic in form and light in colour. The first phase of dolomitization is indicated by complete alteration of the fine-grained carbonate rock into coarser dolomite. The completely dolomitized zones in parts of Balaldev are devoid of free silica. Talc, being the second dominant mineral present in this altered zone, occurs between the interspaces of euhedral dolomite grains and also along their fracture spaces and cleavages. The talc which constitutes about five per cent in the dolomite rock is obviously a younger mineral and hence formed after the dolomite. It represents the second stage in the first phase of hydrothermal activity. Therefore, the first phase is a two-stage process of alteration indicated by (1) the complete dolomitization of the limestones

and subsequently by (2) the formation of talc.

Throughout the copper belt, mineralization is strictly confined to the dolomitized zones, as for example, in the southern, eastern and northern edges of the Balaldev ridge, in parts of Dewaldhar, and also north of Ghirauli and Tamkhani. The dolomitized rocks contain about 85 per cent dolomite, 5 per cent talc and 0 to 5 per cent calcite. The copper mineralization is mostly along the cleavages, fractures (Plate X, Fig. 4) and the intergranular spaces of the dolomite. The ores also replace talc and dolomite in some instances. Occasionally, bands of chalcopyrite as thick as 3 mm occur along the foliation planes of the talc-schist.

All the above features again indicate that dolomitization preceded the formation of talc, after which copper and iron sulphides were deposited. However, no lead ore occurs in these dolomite-talc-schist zones.

(2) Physical changes due to alteration - As a result of hydrothermal alteration, the limestones have undergone distinct and well-marked physical changes. Among the various physical changes, colour and textural variations were the most pronounced. The increase of porosity, permeability and fracturing as a result of dolomitization were also detected through petrographic studies.

a) Colour - Changes in colour of the rocks is probably an important and definite effect of hydrothermal alteration observed in all the localities known for the copper mineralization around Bageshwar. The unaltered limestones are dark grey in colour in contrast to white to ordinary white coloured dolomites, which occur around the copper ores. A narrow and poorly defined transitional zone has been recorded between the limestones and the dolomitized limestones. The rocks of this transitional zone are composed of light

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grey dolomitic limestone in which dolomite crystals form scattered patches.

Hewett (1928, p.829) also observed similar changes in colour due to hydrothermal dolomitization of the limestones in many parts of the world. Lovering (1949, p.22) found similar colour variations in East Tintic district, Utah. Watson (1905) recognised that the dark grey limestones are converted into white and light-coloured dolomites as a result of hydrothermal alteration in Virginia district, U.S.A. About the formation of such light coloured dolomitized zones, Park Jr. and MacDiarmid (1964, p. 143) state, "There is a tendency during recrystallization for the carbonate rocks to expel impurities, such as carbon, thus the resulting rocks are generally whiter than their unaltered equivalents".

b) Texture - The textures of the carbonate rocks within and around the copper deposits at Balaldev, Ghirauli and Tankhani are extremely varied. The completely dolomitized zones are composed almost invariably of extremely coarsely crystalline dolomites (Plate XV, Fig.1). At Balaldev and Ghirauli, some of the dolomite grains have grown upto 5 or 6 mm in diameter. The grains are most characteristically uniform and idiotopic in texture. Thin sections of rocks from the completely dolomitized zones show the following petrographic features:-

The dolomites are colourless to white in colour and show all the characteristic properties of the mineral. The crystals of dolomite have rhombic cleavages and under crossed nicols exhibit beautiful lamellar twinning. Another important feature is that the crystals do not have close contacts, thus, leaving much intergranular space which was later occupied by talc as well as the copper sulphides (Plate XV, Fig.2). Copper mineralization was also observed along the cleavage partings and fracture spaces in the dolomites.

The country rock, adjacent to the envelopes of altered zone shows a remarkable change in grain-size and texture. Actually, the contact here between the dolomites and the less affected carbonate rocks is sharp, although a poorly defined transitional zone has been defined in parts of Balaldev copper deposits on the basis of Ca/Mg ratio which will be discussed later. Megascopically, this transitional zone is composed of fine-grained dolomitic limestone. In thin sections, porphyrotopic texture is always very common. The porphyrotopes of the dolomite euhedra occur in a ground mass of fine-grained calcite. The dolomite porphyrotopes are more fresh and clear than the dull, clouded and dusty calcite. The coarser porphyrotopes of dolomite in the transitional zones range in size from 1.5 to 2.7 mm (Plate XI, Fig.2). These carbonate rocks of the transitional and the altered zone may easily be distinguished by their texture and colour, even in the field.

The distinction between the unaltered or less affected carbonate rocks and those of the transitional zone is rather difficult to ascertain in the field because both are fine-grained and grey to light grey in colour. To some extent the colour variation is very poorly defined, but a little colour difference alone, perhaps, may not be considered as a criterion for their distinction. However, the two rock types may be distinguished on the basis of their petrographic character. The unaltered carbonate rocks are composed of very fine, cloudy and dusty calcite with a few scattered porphyrotopes of dolomite which are lesser in number and smaller in size than those found in the carbonate rocks of the transitional zone. In a few thin sections of the rocks collected from the less affected zones, there are some veins of dolomite. Talc is practically absent in both the transitional and the poorly altered zones.

The above textural observations indicate that in parts of Balaldev ridge, the alteration of limestone to dolomite is a progressive change in which coarsening of the grain size is accompanied by the increase of dolomite content. Regarding similar variation in the texture around the hydrothermal ore deposits, of Europe and North America, Hewett (1928, p.848) says, "With regard to texture, the dolomite resulting from the alteration of limestone is commonly more uniform and more coarsely crystalline".

Lovering (1949) has also pointed out similar increase in the grain size of carbonate rocks through dolomitization. In summarizing his exhaustive study of hydrothermal alteration, Schwartz (1959, p.167) states, "Dolomitized limestones are generally coarser grained than the fresh rocks and unless the relation to the primary limestone can be recognized may appear entirely unaltered".

Ridge (1936, p.301) in discussing the genesis of the Tri state lead-zinc ores, U.S.A., has pointed out that the hydrothermal dolomites are much more coarsely textured than the main mass of the dolomitic limestone. Tarr (1936) noted the significance of coarser dolomite and its replacement by the sulphides in parts of south-eastern Missouri, U.S.A. Ohle (1951, p.650) calls the hydrothermal dolomites as "recrystalline" and his table (p.652) clearly shows that the dolomite percentage of the carbonate rocks increases with increase in grain size. Ohle (1951, p.891) says, "As recrystallization proceeds, the average grain size increases and also the percentage of the total carbonate that is dolomite".

Jicha Jr. (1951, p.719) reported crystals of hydrothermal dolomite upto 1 cm in diameter in the lead-zinc deposits at Cave di Predil, Alpine Europe.

The author believes the observers of the Bageshwar deposits can never fail to be impressed by this striking range in size and shape of the carbonate minerals while examining the altered and unaltered zones. The transitional zone perhaps is difficult to ascertain from their textural characters.

(C) Porosity, permeability and fracturing - For the last 30 years, the problem of the increase in porosity, permeability and fracturing through dolomitization has been a subject of interest because of the economic potentialities of the dolomitized rocks in many parts of the world.

In the present work, the petrographic and textural studies of the carbonate rocks from the altered and unaltered zones revealed that dolomitization was accompanied by a progressive increase in the porosity, permeability and fracturing of the rocks. No absolute measurement of porosity or permeability was, however, attempted.

The dolomites from the altered zones of Baleldev-Ghirauli are more frequently fractured and jointed than the unaltered limestones from the same localities (Plate XV, Figs. 1 and 3). Another important feature of the altered zone is the abundance of micro-vugs and wide interspaces between the dolomite crystals.

Megascopically, the carbonate rocks of the transitional and poorly affected zone, are practically free from fractures and vugs. Thin sections of the dolomitized portion of the rocks show that the aggregates of dolomite porphyrotopes are much fractured and loosely held together. The unaffected limestones, on the other hand, have very few fractures and micro-vugs, and consist largely of fine-grained and densely packed calcite. The above features, thus, clearly indicate that dolomitization has not only made the rock more fractured but also increased its porosity and permeability. It is believed that for a comparative study to detect the increase in porosity and permeability through dolomitization, thin sections from the transitional zones are ideal, as the variation is easily marked even in a single thin section. Due to favourable structural condition there is a greater concentration of ore in the completely dolomitized zones, which are highly fractured and vuggy with numerous open spaces and cavities. In some instances, the copper sulphides have also replaced the carbonate minerals and talc to some extent.

Martin (1958, see Schwartz, 1959, p.167) while suggesting a relation between alteration and loss of competency, has emphasized that the intensity of shattering is directly proportional to alteration and the unaltered rocks seem to lack the intense shattering. He suggests a genetic relation between fracturing and alteration. Lovering (1949) also upholds the view that the hydrothermal dolomites are much more fractured and jointed than their unaltered equivalents. Currier (1935) is of the view that the dolomitized portions of the limestones are the sites of greatest shattering in the carbonate country rock.

The subject of porosity and permeability through dolomitization has very recently been developed particularly by the petroleum geologists, mining geologists and economic geologists in U.S.A., U.S.S.R. and U.K.

Tarr (1936, pp.841-42) also noted an increase in porosity and permeability of the carbonate rocks through dolomitization. Hewett (1928) observed that the hydrothermal dolomites were more porous than their unaltered equivalents. Recently, Murray (1960) in his classic paper on the origin of porosity in carbonate rocks has investigated the petrographic evidence for the relationship between porosity and dolomitization. He states, "As the dolomite content increases above 50 per cent, the porosity rapidly increases to value approximately 30 per cent at 80 to 90 per cent dolomite ... Porosity and pore size increases as complete dolomitization is approached". Ohle (1951) in his excellent work on permeability and dolomitization has clearly stated that the high percentage and coarse granularity of dolomite tremendously increases the permeability of the dolomitized zones. He also measured an average increase in permeability of over 18,000 per cent in the carbonate rocks due to dolomitization.

(3) Mineralogical changes

The mineralogical changes around the copper deposits of Balaldev, Ghirauli and Tamkhani, are more distinct and extremely varied. These variations are partly discussed under textures and zoning later in this chapter.

On the average, the dolomitized rocks have the following percentage composition:

Dolomite	-	85 to 90 per cent
Calcite	-	0 to 5 per cent
Talc	-	5 to 7 per cent

Characteristically, the carbonate rock with the above mineral composition is extremely coarsely crystalline and idiotopic. Intimate associations of the copper ores with the altered rocks having the above composition and a textural code,(C^3i 080)with 5 per cent talc, is a remarkable feature observed wherever copper was located in this region. Talc was never found in association with the unaltered or less altered carbonate rocks. No rock in the less altered or transitional zone is however, free from dolomite. The variation of dolomite in these zones is being discussed by the author under the title 'zoning'. Again an important observation in this respect is that a decrease in the dolomite content is reflected by an increase in the Ca/Mg ratio from the completely dolomitized zone to the barren zone (Fig. X). In the dolomitized zones, where the alteration is complete, it is rather difficult to find a clear out evidence indicating the replacement of calcite by dolomite. Thin sections of these rocks show only coarse dolomite grains. But in the transitional zones, the evidence for the replacement of calcite by dolomite is quite clear.

(4) Summary and the sequence of the mineral formation

The petrographic studies and the field relations of the rocks suggest that the first phase of hydrothermal activity leading to the deposition of copper at Bageshwar has been amply indicated by the complete dolomitization of the carbonate rocks and the formation of some talc in these altered rocks surrounding the copper ores. The dolomitized zones are invariably composed of white and creamy white dolomite-talc rock with the compositional and textural symbol (C^3i 080). A little of talc is also associated with these rocks. A poorly defined transitional zone, about 4 to 5 ft. wide may extend from the completely altered to poorly altered zones. In the transitional zone the porphyrotopes of dolomite are larger in grain size and greater in number than the unaltered carbonate rocks.

As for the sequence of formation of the dolomite, talc and copper ores is concerned, the petrographic studies clearly indicate that the original fine grained carbonate rocks were converted into coarse dolomites due to hydrothermal activity. The second stage of alteration, which is restricted to the dolomitized zones, is the formation of talc along the fractures and rock cleavages of the dolomite. The sulphides (pyrite, chalcopyrite) are confined only to the dolomitized and the talc horizons. The mineralization is mainly of the fracture, vein and pore space filling type. Replacement of dolomite and talc by copper sulphide on a minor scale is also an important fact. According to the above discussion on the events of mineral formations, the paragenetic sequence of the copper-bearing rocks may be interpreted as follows:

Time

Dolomitization
Formation of talc
Sulphide Cu-Fe mineralization

b) Second phase

(1) Why a second phase? Some of the most unique features of the base metal deposits of Bageshwar are given in the following lines:

i) The occurrences of galena and the sulphides of Cu-Fe were recorded from the same localities such as at Balaldev, Shishkhani-Chhanapani copper-lead belt and also at Devaldhar.

ii) The host rocks of the copper mineralisation are talc-dolomite rock and talc-schist, whereas lead mineralization is confined only to the silicified dolomitic limestone.

iii) The complete absence of any lead ore within the body of copper ores and vice versa is a remarkable feature of these sulphide deposits.

Now, if a single phase of hydrothermal activity was involved, it would be difficult to explain for the occurrences of ores of copper and lead separately from the same localities. Also, if a single phase is envisaged for the deposition of the ores, then copper and lead ores should have been encountered together in at least one of the localities. Since the mineralogy of the copper ores as well as their corresponding wall rocks differ from those of the lead ores to a considerable extent, only two phases of hydrothermal alteration and ore deposition may perhaps explain this mineralogical diversity. It is, therefore, logical to advocate that the hydrothermal solution which contributed copper was not responsible for the deposition of lead. In other words, the occurrences of copper and lead may be accounted for if two different phases of hydrothermal activity are envisaged. The complete absence of talc, incomplete dolomitization and intense silicification of the lead-bearing rocks indicate that the temperature and composition of the hydrothermal solutions were somewhat variable.

It is important here to note that the deposition of galena in the silicified dolomitic limestones was mainly along fracture, vein and slip planes. Galena is also disseminated in the silicified limestone although on a minor scale. There is ample megascopic as well as microscopic evidence of brecciation, fracturing and subsequent veining of the host rocks by galena. From such evidence one can easily visualise that the country-rocks were fractured and brecciated after the earlier hydrothermal activity leading to copper mineralisation but prior to the second activity which deposited lead. It is, therefore, reasonable to argue from the available mineralogical and chemical evidence that the hydrothermal solution which altered the wall rocks first and deposited copper was certainly not the same which was responsible for the later silicification and deposition of lead with a certain time gap between the two periods of mineralization. It cannot, however, be stated clearly whether or not the source of the solution was the same.

Lindgren (1928, p. 521-524) suggested that the successive phases of mineralization were a common feature of epithermal deposits and the fracturing and brecciation of the epithermal minerals may be followed by the deposition of an entirely new suit of minerals. Ridge (1936) recognised two successive phases of hydrothermal activity on the basis of the diversity in mineralogy of the sulphide ores, while discussing the genesis of the Tri-State lead-zinc deposits, U.S.A. Lovering (1967, personal communication) also gave support to the second phase of hydrothermal activity for lead deposition at Bageshwar.

(2) Stages of mineral formation

The carbonate rocks associated with the lead deposits indicate that dolomitization, silicification and the deposition of lead were the three main events which were involved in the second phase of hydrothermal activity in the Balaldev, Chhanapani, Shishkhani copper-lead belt.

Three main sequence of events involving different types of alterations and deposition of lead ores in the second phase of hydrothermal activity are tabulated below:

Time

Dolomitization (incomplete)
Silicification
Lead mineralization

Incomplete dolomitization : In thin sections, the lead bearing carbonate rocks generally show porphyrotopic euhedral aggregates of dolomite set in a fine calcite matrix. According to Friedman (1965, p. 652), Murray (1960, p. 73), Carozzy (1960, p. 283), Ohle (1951, p.883), Van Tuyl (1916) and others, this occurrence of isolated and coarser dolomite euhedra in finer calcite is one of the salient features of incomplete dolomitization.

<u>Silicification</u>: Silicification of the carbonate rocks is perhaps one of the most important processes involved in the second phase of hydrothermal activity in these lead deposits. Here, silicification is represented mainly by the presence of jasperoid which partly replaces both calcite and dolomite (Plate XV, Fig. 4) and ~~some~~ also veins of quartz. There are also some replacing veins and voids of jasperoid which contain a few unreplaced relict of calcite and dolomite (Plate XVI, Fig. 1). However, the silica replacing the carbonates is more fine-grained than that which filled up open spaces in the same rock (Plate XVI, Figs. 2,3). Accordingly, their textures are somewhat different. Two varieties of silica have been recorded: (1) coarse-grained quartz occurring in micro veins, vugs and voids showing well-developed crystal out lines; (2) fine-grained jasperoid replacing the carbonates. The fine-grained carbonates are again more completely replaced by jasperoid than the coarser ones. Regarding the relative time involved in the formation of the two texturally different varieties of silica nothing can be said definitely. It is, however, evident that dolomitization of the carbonate rocks helped the formation of minor open spaces in the form of micro vugs and micro voids which were later filled by silica (Plate IX, Figs. 1,2, Plate XVI, Fig. 1). Galena, being an intimate associate of jasperoid also occupies some of the veins, fractures and open spaces in which the latter occurs (Plate IX, Fig. 3). The galena-jasperoid relations, as described in the chapter on Mineragraphy and Paragenesis (p.110) indicate that silicification preceeded the deposition of galena.

The following evidence supports a replacement origin for the jasperoid: (1) the silicified portions of the carbonate rocks usually contain relicts of calcite and dolomite; (2) the contacts between calcite-jasperoid and dolomite-jasperoid and more particularly, those between calcite and jasperoid are extremely ragged and irregular displaying 'eating away' phenomenon; (3) there are numerous rhombic jasperoid pseudomorphs after dolomite.

B. Ore Zoning

1. Introduction

An attempt has also been made here to investigate the Bageshwar sulphide deposits from the point of view of zoning.

Zonal distribution of hydrothermal minerals around centres of comparatively high temperature minerals is a known feature in many of the epigenetic ore deposits.

Park Jr. (1955) has thoroughly reviewed the subject on the zonal theory of ore deposits and Schwartz (1955, p. 319) pointed out the significance of the hydrothermally altered zones as guides to searching for ore.

To define the subject the author cannot do better than to quote here Park Jr. and MacDiarmid (1964) as follows:"The paragenesis of mineral formation in moving ore fluids produces changes in ore mineralogy along the course of deposition. Such changes are described as zoning, and are found in sedimentary deposits are well as in magmatic and metamorphic ores. In the ideal case of radiating hydrothermal or pneumatolytic fluid, changes in chemistry,temperature and pressure along the fissures result in the deposition of different minerals in concentric zones at increasing distances from the magmatic source".

2. Previous investigation

Roy Chowdhry, Subramanyam and Banerjee (1960) arbitrarily suggested zoning in the Shishkhani-Chhanapani belt of copper and lead. The only statement made by them in this respect is that "the different topographic levels at which galena and chalcopyrite occur

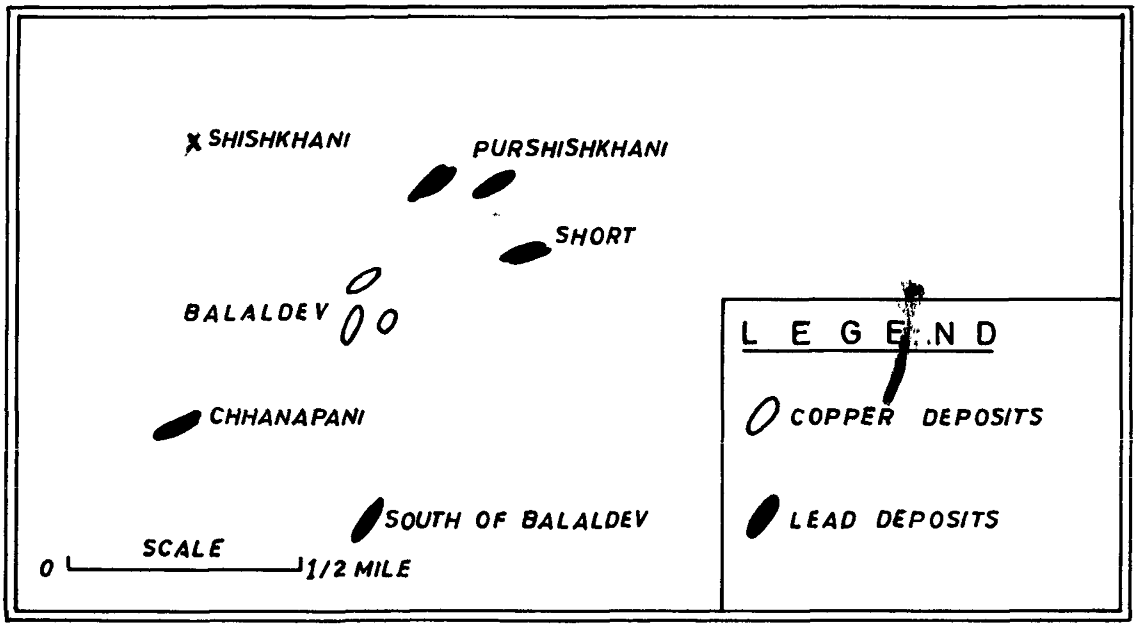


FIG. 9. ZONAL DISTRIBUTION PATTERN OF COPPER AND LEAD DEPOSITS, SHISHKHANI–CHHANAPANI–BALALDEV BELT, ALMORA DISTRICT

2

would perhaps suggest zoning ..."

With the exception of the above authors, none of the earlier workers reported any type of zoning from the area under review.

3. Zoning in the Bageshwar deposits -

After a careful investigation of the sulphide deposits of Bageshwar, the author recognised two types of zoning viz., (i) the district zoning; (ii) zonal distribution of Ca/Mg ratio, SiO_2 and CO_2 around copper deposits.

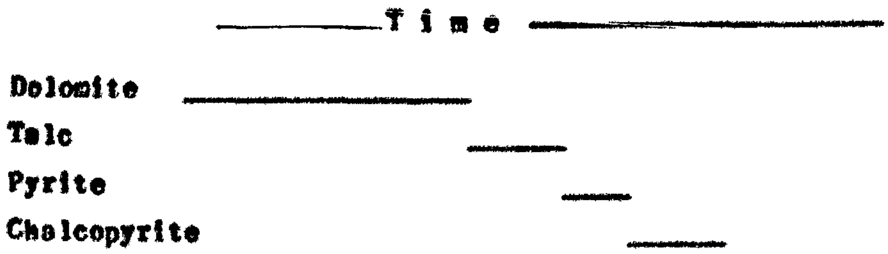
i) District Zoning :

The deposits in the centre of the Shishkhani-Chhanapani-Balaldev belt (located at Balaldev ridge) are characterized by the pyrite-chalcopyrite assemblage. The peripheral deposits (situated at Purshishkhani, Short, Chhanapani and south of the Balaldev ridge) contain galena as the only lead sulphide ore. The distribution of above copper and lead deposits is presented in Fig. 9. On the basis of the mineralogy, the mineralized area (of about 2.5 sq. miles) has been divided into two distinct zones: I. the pyrite-chalcopyrite zone and II. the galena zone, surrounding the former.

Zone I : The pyrite-chalcopyrite zone

The pyrite-chalcopyrite zone is located at Balaldev ridge and includes three old workings. The host rocks are essentially dolomite and talc-schist. The zone is defined by the occasional presence of pyrite and chalcopyrite as the primary sulphide minerals. Associated supergene sulphides are covellite and chalcocite. Cuprite, malachite, azurite and limonite are the other ore minerals present. Associated gangue minerals include dolomite with a very little amount of talc and calcite. Free silica is rather absent in this zone. The pyrite-chalcopyrite associated with talc-schists have also been included in this zone.

The sequence of copper and iron sulphide mineralisation and the associated gangue minerals in this zone should be as follows:



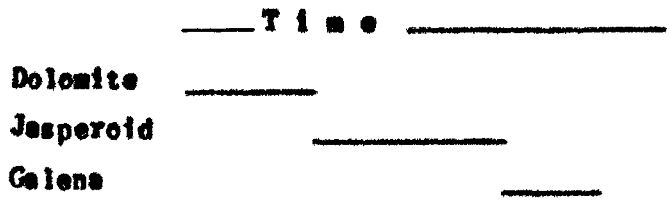
Zone II : The galena zone

The galena zone characteristically surrounds the pyrite-chalcopyrite zone and occurs at five places (Fig. 9). The galena zone is marked by the presence of galena and complete disappearance of pyrite and chalcopyrite. Jasperoid, dolomite and calcite are the principal gangue minerals associated with the ore. In the absence of any mining operation since a very long time, the exact boundary between the two zones is rather difficult to ascertain in the field. The zone is distributed over the following localities surrounding the Balaldev copper zone.

a) Pur Shishkhani, about 3 furlongs north east of Balaldev ridge. There are two main ancient workings.
b) Short (about 3 furlongs E.N.E. of Balaldev ridge).
c) South Balaldev (about 4 furlongs south of Balaldev ridge).
d) Chhanapani (about 5 furlongs southwest of Balaldev ridge).

In all the above localities, the host rock for galena is the silicified dolomitic limestone.

The sequence of mineralization of the hypogene minerals occurring in this second zone is presented as follows:



Discussion

The pattern of ore-mineral distribution indicates that the copper and lead ores at Shishkhani-Chhenapani-Baleldev area are zoned laterally; the central pyrite-chalcopyrite zone occupying the Baleldev ridge is surrounded laterally by the galena zone. No observation on vertical zoning could be made, even if present, because neither the area was ever drilled for sampling nor the ancient workings were reopened for mining in recent years.

The deposits of the Zone I (central zone) are characterised by the presence of dolomite, talc, pyrite and chalcopyrite with some supergene chalcocite, covellite, cuprite, etc. The minerals of this zone are considered to be related to the first stage hydrothermal activity which was responsible for copper mineralisation.

In the Zone II (outer) jasperoid, dolomite and galena have been encountered. A small amount of anglesite is also present as a result of oxidation of galena. The minerals of this zone are believed to be related to the second stage hydrothermal activity which was responsible for lead mineralization.

Therefore, the two zones, described above, correspond to the two stages of hydrothermal activity. Park Jr. (1955) has repeatedly emphasised the fact that the paragenetic sequence of ore minerals is essentially the same as the zoning sequence. Similar central and peripheral distribution of different sulphide ores with associated gangue minerals have been described by Sales (1950). Tom G. Lovering (1969, personal communication) also gave support to the author's contention of district zoning in the Bageshwar deposits.

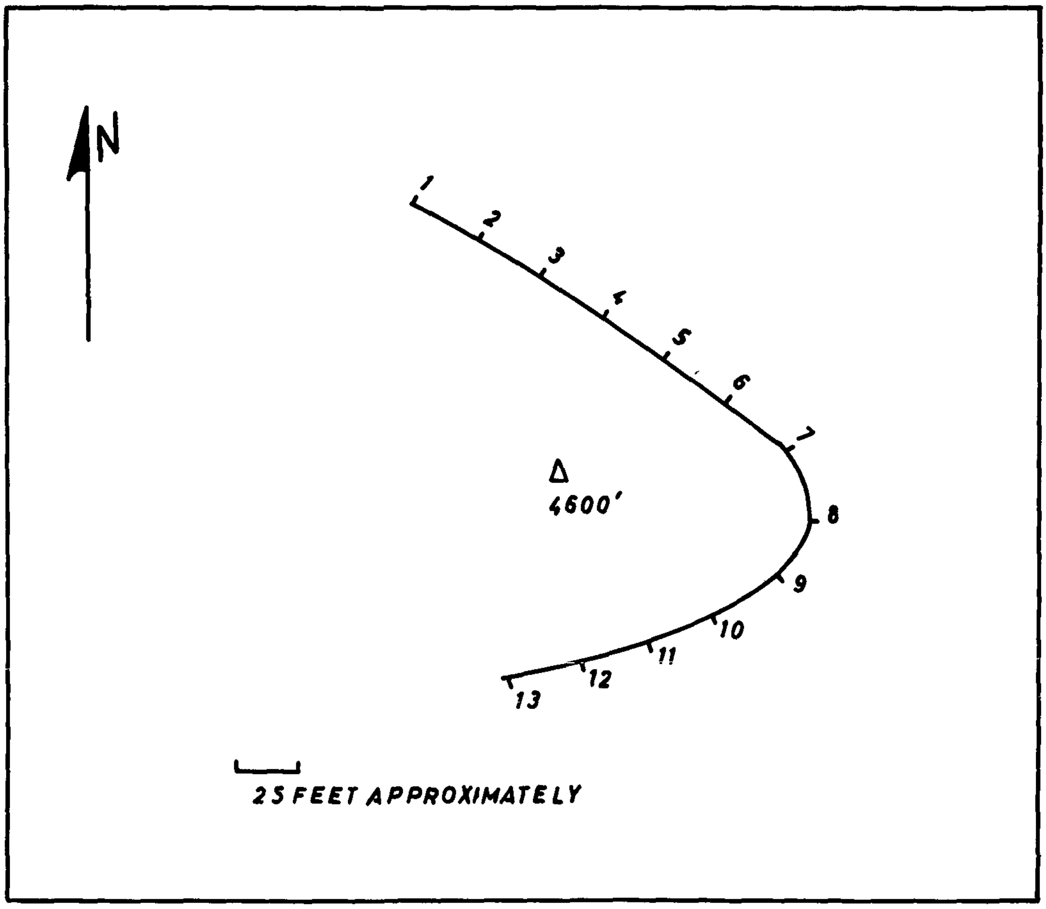


FIG. 10. SAMPLING STATIONS OF CARBONATE ROCKS
BALALDEV RIDGE, BAGESHWAR AREA.
ALMORA DISTRICT

Park Jr. (1955) in his classic paper on zonal theory has mentioned about the central (iron-copper zone) and the peripheral (galena-cinnabar zone). He further (1955, p. 231) stated that the ore minerals deposited near the igneous controls or heat controls are generally more soluble than the minerals farther away; and that the iron-copper minerals which are relatively more soluble are generally deposited in the central zone with galena and cinnabar in the peripheral zones.

ii) Zonal distribution of Ca/Mg ratio, SiO_2 and CO_2 around copper deposits

A prilIminary geochemical study of the carbonate rocks around some of the copper deposits of Bageshwar was made in order to ascertain whether or not they show any evidence of zonal distribution of these major chemical constituents. For this purpose samples were collected from the adjacent parts of the Balaldev copper bearing ridge.

Method of approach

Sampling - The only possible way was to collect samples (at regular intervals of 25 ft.)along a contour roughly lying between 4,200 and 4,400 ft. above sea level. The old workings of copper ores are located in the northern, eastern and southern edges of the Balaldev ridge. A traverse from the northern edge to the eastern edge of the ridge was taken. The dip of the beds is 50°N 45°W. Sample numbers 1,2,3,4,5,6,7 and 8 were collected along this traverse. The sample numbers 9, 10,11,12 and 13 were collected from the eastern to the southern sides of the ridge. The three ore bodies in the old workings are located at stations 4, 8 and 13., in the northern, eastern and southern sides of the ridge respectively. The traverse localities and corresponding numbers are shown in Fig. 10.

TABLE - VI

Results from chemical analysis of carbonate rocks around Balaldev ridge

Sample No.	CaO	MgO	CaO/MgO	Ca	Mg	Ca/Mg	CO_2	SiO_2
1	28.74	19.12	1.503	20.54	11.52	1.780	43.21	7.02
2	30.46	20.19	1.508	21.77	12.17	1.786	45.82	2.02
3	29.96	20.84	1.43	21.42	12.56	1.703	45.86	1.94
4	29.72	21.31	1.39	21.24	12.84	1.65	46.27	1.60
5	30.44	19.81	1.53	21.76	11.94	1.82	45.31	2.70
6	27.43	17.52	1.56	19.61	10.56	1.855	41.15	11.04
7	27.05	18.61	1.45	19.34	11.22	1.72	41.31	10.34
8	28.66	20.24	1.41	20.49	12.20	1.67	44.36	4.10
9	26.71	19.06	1.401	19.09	11.49	1.65	41.58	10.60
10	21.11	13.47	1.56	15.09	8.12	1.85	31.04	32.32
11	16.86	12.02	1.402	12.06	7.24	1.66	25.04	43.58
12	20.50	13.65	1.501	14.66	8.23	1.77	30.79	32.70
13	29.62	21.30	1.39	21.16	12.84	1.65	46.26	1.52

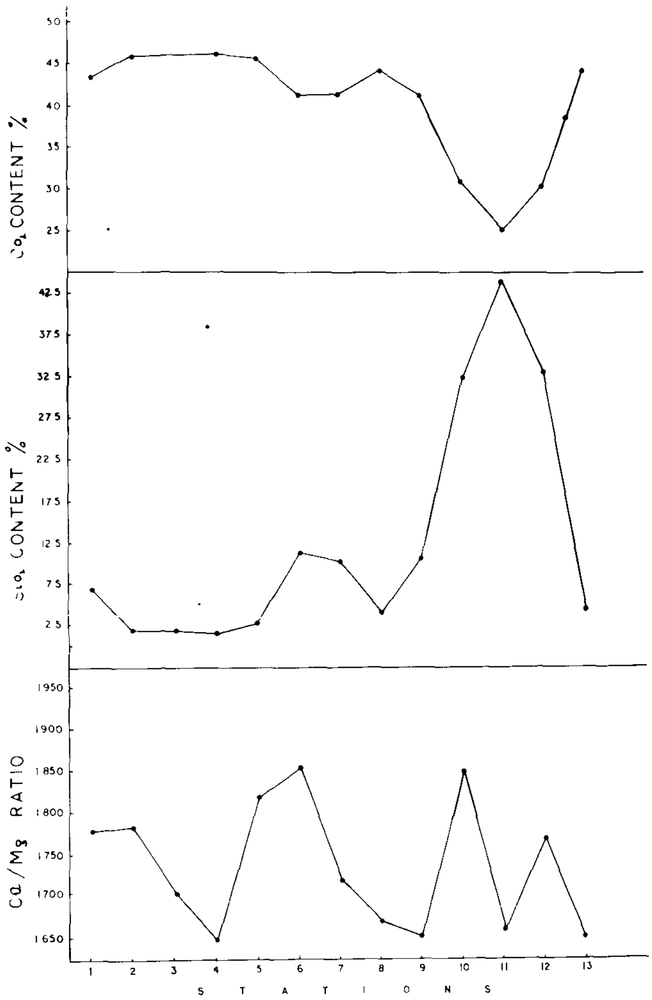


FIG 11 VARIATION DIAGRAM OF Ca/Mg RATIO, SiO_2 & CO_2 CONTENT IN CARBONATES AROUND THE COPPER DEPOSITS OF BALALDEV RIDGE, BAGESHWAR, U.P.

The chemical analysis of all the thirteen samples was done by the Geochem Laboratories, Bombay.

Preparation of graphs - Ca/Mg and CaO/MgO ratios were calculated for each sample (Table VI). The data so obtained were plotted graphically (Fig. 11) to show the relative variation of certain elements or chemical constituents outward from the centres of mineralization. Abscissa of the graph shows the location of samples, and ordinates, the relative amounts of the variables present. In order to have the curves of approximately the same size, scales of the ordinates have been varied accordingly. Graphs were plotted only for those variables which indicate significant and comparatively regular trends. Variables that are erratic in trends or constant or have too small values were omitted.

Ca/Mg distribution : It is evident from the graph (Fig. 11) that the Ca/Mg ratio goes down to 1.65 and 1.67 in the ore bodies shown at 4, 8 and 13 in the graph. The lower value of Ca/Mg ratio at station 12 probably indicates "a false guide" of false zoning which will be discussed later.

The progressive decrease of Ca/Mg ratio from stations 1 and 2 to station 4 indicates a progressive increase in the dolomite content of the host rock towards the ore body. On the basis of the Ca/Mg ratios the carbonate rocks at stations 1, 2 and may may be classified as "slightly calcareous dolomites" (see Chilingar, 1957, p. 187). The carbonate rocks at station 4 (point A in Graph) with a Ca/Mg ratio of 1.65 fall under the group "dolomite" of Chilingar's classification (1957). Then again at stations 5, 6 and 7 there is a progressive increase in Ca/Mg ratio away from the ore bodies as located at stations 4 and 8. Compositionsof the carbonate rocks at stations 5, 6 and 7 are slightly calcareous dolomite. At station 13, where one of the ore bodies is located, the Ca/Mg ratio once again goes down.

SiO_2 distribution : The distribution of SiO_2 in these thirteen carbonate rock samples is also interesting. From Fig. 11 it is evident that a progressive decrease of Ca/Mg ratio is marked by a progressive decrease of SiO_2 content towards the ore bodies, which are located at A, B and D. The high SiO_2 content varying from 43 to 32 per cent with a low Ca/Mg ratio of 1.65 and 1.77 at stations 11 and 12 respectively is anomaleus. This high SiO_2 content is obviously due to silicification of both calcite and dolomite. It has been pointed out in the earlier section of this chapter and in the chapter IV that calcite is more susceptible to silica replacement than dolomite. So, it appears that much of the calcite content of the rock was replaced by SiO_2 and hence the ratio Ca/Mg was considerably lowered down. Another important relationship that exists between the SiO_2 and CO_2 distribution is the increase of SiO_2 content with the corresponding decrease of CO_2.

Interpretation : This type of variation of Ca/Mg or CaO/MgO ratios, and CO_2 and SiO_2 content around the copper ore bodies at Balaldev ridge is highly suggestive of a regular zonal distribution of the above constituents. It is also evident from the chemical analysis data that the country rocks surrounding the ore-bodies at Balaldev ridge, in almost all cases, have obviously been chemically affected. The intensely affected zones, within which the copper sulphides occur have the following chemical nature:

(1) Lowest values of Ca/Mg ratios (1.65 - 1.67);
(2) SiO_2 content is low and not more than 2 to 4 per cent;
(3) The CO_2 content has the highest value (about 46 per cent).

The above three features of the carbonate rocks in these most intensely altered zones indicate that the rocks are mainly "dolomitic" in composition. Comparing the values of CaO/MgO ratios of these rocks with Frolova's (1959) values, it appears that the CaO/MgO ratio of the carbonate rocks at stations 4 and 13 have a slightly lower value (.01). This slightly lower value of CaO/MgO ratio is due to the formation of talc, which might have also utilised all the SiO_2 content of the formation. Thus, the mineralogical composition of the intensely altered zones, as reflected by the chemical analysis, is dolomite with a very little of talc. Accordingly, decrease or increase of certain chemical constituents (Fig.11) around the ore bodies was recorded as follows:

(1) The Ca/Mg or CaO/MgO ratios progressively decrease towards orebodies.

(2) The CO_2 content progressively increases towards ore bodies.

(3) The SiO_2 content progressively decreases towards ore bodies.

The above mentioned facts further confirm that the distribution of Ca/Mg, CO_2 and SiO_2 follow certain zonal pattern.

Application : The application of the variation diagrams (of known ore bodies) in finding unknown deposits is evident from the graphs. Similar diagrams may be plotted in suspected regions and the results may be compared with those noted for known deposits. The present results would probably have been more useful and applicable if some drill hole samples were available for chemical analysis.

C. Guide to Ore Deposition

Application of certain important observations made by the author during the geologic study of the area under review may prove to be of some value in prospecting and locating new base metal deposits in this region. In the following suggestions some probabilities are pointed out:

1. Gangue minerals - The associated gangue minerals are generally regarded as the useful guides in mineral prospecting. For example, there is no trace of copper ores in the rocks which are free from dolomite and talc. Only the white and coarse-grained idioptic dolomite and talc-dolomite rock hosted the copper ores. Similarly, it is logical to consider the jasperoidized zones as the favourable guides for lead deposits. The presence of numerous voids, vugs, veinlets, etc. in the jasperoids associated with the carbonate rocks may also be regarded as a valuable guide to the localization of lead ores.

2. Favourable host rock - Among the three major types of metasedimentary rocks namely, slates, limestones and quartzites which occur in the area under review, only the carbonate rocks were found to be the most favourable environment for the deposition of copper as well as lead. They were also found to be most susceptible to dolomitization and silicification through hydrothermal alteration.

3. Zonal distribution pattern - Further, from study of the zonal distribution pattern of the sulphide deposits of Bageshwar, it may be suggested that prospecting for copper deposits should preferably be made within areas around which there are lead occurrences and vice versa.

Chapter - VI

MINERAGRAPHY AND PARAGENESIS

Introduction

No systematic mineragraphic study of the copper and lead ores of Bageshwar has been made in the past. All the previous workers, including Jhingran and Mathur (see Roy 1961), Subramanyam and Jain (1961) and Roy Chowdhry et al.(1960) described the mineralogy of the ores on the basis of their megascopic characters. Nautiyal (1962) studied only a few polished sections of copper ores from the Almora and Pithoragarh districts, Uttar Pradesh. His descriptions do not deal much with the mineragraphy and paragenesis of the various ore forming minerals. Rasul and Sharma (1963) made a brief study of some polished lead ores collected from Chhanapani, Bageshwar, Almora District.

The present author has undertaken for the first time a detailed ore microscopic examination of the copper and lead ores from the Shishkhani-Chhanapani-Balaldev belt, and also of the copper ores from Ghirauli, Tamkhani and a few more localities in the Bageshwar area. This attempt was made with a view to determine the mineral assemblages of the ores, their texture and paragenetic sequence. The Vickers hardness number for some ore minerals was also determined.

Collection of samples - The ancient workings of the copper and lead ores are generally confined to the limestone horizon of the calc-zone of Bageshwar. There are in all nine distinct old workings of copper ores and ten old workings of lead ores distributed all over the area. All the mines which are in the form of narrow trenches are partly submerged under water. No attempt has yet been made to reopen the old workings since none of the deposits was found to be economical so far. As far as possible, care was taken to collect the samples of copper and lead ores from the approachable sections of the workings and also from the mineralised portions of the outcrops. About 50 representative samples both of copper and lead ores were carefully selected for the present study.

Mineralogical descriptions of the ores

Mineralogical descriptions of the various copper and lead ores, which have been identified in the polished sections under reflected light, are given below:

1. Pyrite (FeS_2)

Pyrite is present in the mineralized zone of talc-schist horizon in the Balaldev-Shishkhani region. It is likewise present, but to a lesser extent, in the copper deposits associated with the dolomitized zones of Balaldev ridge. In a few polished sections of the copper ores, pyrite is completely absent. Almost without any exception, pyrite is partly or wholly replaced by chalcocite. There are some irregular and larger inclusions of talc and dolomite in pyrite.

Colour - yellowish white and sometimes creamy
Polishing behaviour - moderate;
Cleavage - cubic
Reflectivity - higher than the surrounding minerals that include chalcopyrite, chalcocite, etc.

Crossed nicols - isotropic.
Hardness - H_v = 1195.3.

<u>Etch test</u>
Positive reaction: HNO_3 - slowly effervesces.
Negative reaction: HCl, KCN, $FeCl_2$, KOH, $HgCl_2$

2. <u>Chalcopyrite</u> ($CuFeS_2$)

Chalcopyrite happens to be the only primary copper mineral found in the deposits. It occurs both in the completely dolomitized zones as well as the talc-schist horizons of the Balaldev ridge. Chalcopyrite is quantitatively the most important ore mineral. Some ore specimens are made up largely of massive chalcopyrite, but in others chalcopyrite has some disseminated pyrite grains. Occasionally, talc and dolomite occur as gangue inclusions. Chalcopyrite has been partially replaced by covellite and chalcocite.

Colour - bright yellow and yellow with a shade of green.
Reflectivity - approximately equal to pyrite and more than chalcocite etc.
Anisotropism - poorly defined with polarization colours of greenish yellow with greyish tint.
Hardness - H_v = 190.6

<u>Etch test</u>
Positive reaction: HNO_3 - Fumes tarnish
Negative reaction: HCl, KCN, $FeCl_2$, KOH, $HgCl_2$

3. <u>Covellite</u> (CuS)

Covellite is a minor but an important constituent of the copper ore deposits of Bageshwar. Its occurrence was not reported by the earlier workers. It ranks third in abundance of the copper sulphides.

Colour - deep blue with violet tint; also pleochroic with shades of violet blue colours;

Reflectivity - lower than chalcopyrite, approximately equal or slightly more than the greyish-white chalcocite.

The mineral is markedly anisotropic with yellowish colours.

Etch test

Positive reaction : HNO_3 - Fumes tarnish
KCN - Stains black

Negative reaction : HCl, $FeCl_2$, KOH, $HgCl_2$

4. Chalcocite (Cu_2S)

Chalcocite is a common copper ore mineral. It was identified in all the polished sections of copper ores and ranks second in abundance as compared to chalcopyrite. The replacement of covellite, chalcopyrite and pyrite by chalcocite displays various textures of supergene sulphide enrichment zone.

Colour - White with bluish tint or bluish white with greyish tint. The chalcocite replacing pyrite is commonly white with bluish tint and that formed due to the chemical alteration of chalcopyrite or covellite is bluish white with greyish tint. This colour variation was found to be of some use in recognizing the original minerals. Chalcocite also forms a pseudomorph after cubic pyrite.

Reflectivity - Less than chalcopyrite.

Form - typical reticulating vein texture.

Isotropic under crossed nicols, but in a few other cases, a feeble anisotropism was also observed.

Hardness - $H_v = 89.62$

Etch test

Positive reactions : HNO_3 - Effervesces vigorously, stains blue.
HCl - Tarnish faintly.
KCN - Quickly stains black.
$FeCl_2$ = Stains blue.
$HgCl_2$ - Tarnish faintly.

Negative reaction : KOH

5. Cuprite (Cu_2O)

Cuprite, being an abundant oxide of copper, invariably replaces the earlier sulphides viz., chalcocite and covellite. Cuprite, in turn alters into malachite and some unidentified black ore (probably copper pitch).

Colour - bluish grey or greyish blue; sometimes giving rise to earthy and ruby red powder.

Reflectivity - approximately equal to chalcocite.

Crossed nicols - cuprite shows characteristic deep red internal reflection.

Etch test

Positive reaction : HNO_3 - Effervesces
HCl - Turns brown after long etching.
KCN - turns brownish.

Negative reaction : $FeCl_2$, $HgCl_2$.

6. Malachite $CuCO_3.Cu(OH)_2$

The earlier workers reported the occurrence of malachite in Almora and Pitheragarh districts. Malachite was recognised in almost all the polished sections of copper ores. Malachite is probably the most abundant mineral of the oxidized zone. It veins as well as replaces both chalcocite and cuprite. Malachite in turn, has been veined and replaced by azurite and limonite.

Colour - grey with greenish tint.

Reflectivity - low, higher than gangue and lower than chalcocite and cuprite.

Pleochroism - Well-marked.

Internal reflection - well defined with green colours.

7. Azurite $2CuCO_3.\ Cu\ (OH)_2$

Azurite is comparatively a rare carbonate of copper. The mineral occurs in the vugs and open spaces in the oxidized ores. There is no instance of direct replacement of the sulphide minerals by azurite.

Colour - deep greyish blue, earthy in appearance;

Reflectivity - low, slightly higher than the gangue and lower than chalcocite.

Crossed nicols - beautiful blue colour is the characteristic feature of the mineral.

8. <u>Limonite</u> ($2Fe_2O_3 . 3H_2O$).

Limonite is associated with some of the polished sections of copper ores. The common associates of limonite were found to be malachite, pyrite and sometimes chalcopyrite.

Colour - grey and greyish white;
Reflectivity - low, earthy looking;
Pleochroism - slight;
Anisotropism - present, but masked by yellow and brown internal reflection.

9. <u>Galena</u> (PbS)

Galena is the only sulphide mineral present in the lead deposits of Shishkhani, Short, south of Baleldev ridge, Chhanapani, etc. in Bageshwar. It occurs in the veins, cleavage partings, fractures, vugs and other open spaces in the silicified dolomitic limestones. Jasperoid, dolomite and calcite are the associated gangue minerals. Sometimes galena occupying fractures and cleavages of the country-rocks alters into anglesite.

Colour - pure white or galena white;
Reflectivity - high;
Cleavages - well defined, the intersection of the cleavages is marked by triangular pits, which is the most characteristic feature of galena.
Crossed nicols - perfectly isotropic.
Hardness - H_v = 81.60

<u>Etch test</u>

Positive reaction : HNO_3 - Effervesces and turns black.
HCl - Tarnish iridescent
$FeCl_2$- Stains iridescent

Negative reaction : KCN, KOH, $HgCl_2$.

10. <u>Anglesite</u> ($PbSO_4$)

Anglesite occurs along cleavages and fractures in galena.

Colour - grey and brownish grey;
Reflectivity - low, approximately equal or slightly more than the gangue.
Anisotropism - well-marked.

<u>Textures and micro-structures</u>

The study of the polished ore-specimens under reflected light has revealed many interesting textures in the copper and lead ores. Different types of "replacement" and "vein filling" textures characterise some of these ores. To a lesser extent vein filling textures are developed in the copper ores. Galena shows both disseminated and vein filling textures, but it appears that the vein filling has played an important role in the deposition of this mineral.

Following are the four major types of textures, observed in the copper and lead ores of Bageshwar:

A) Automorphic outlines (Bastin 1950).
B) Vein filling, fracture filling (Schwartz, 1951).
C) Replacement textures
   1. Rim replacement (Schwartz, 1951, p.589; Edwards, 1960, p.177 or centripetal replacement (Lindgren, 1933, p.184).
   2. "Ice cake" texture (Schwartz, 1951, p.589).
   3. Relict texture.
   4. Pseudomorphic replacement texture (Park Jr. & MacDiarmid, 1964, p.114).
   5. Reticulating texture (Schwartz, 1951, p.590) or Mesh pattern (Bateman, 1930, p.401).
D) Colloform texture.

The textural relationships observed between the pairs of groups of ore-minerals, are described as follows:

1. *Pyrite and chalcopyrite*

Pyrite and chalcopyrite are the only primary sulphides recognised in the suite of copper ores examined. Pyrite occurs as aggregates of more or less corroded cubic and sometimes, as rounded grains surrounded by chalcopyrite. In majority of cases, pyrite-chalcopyrite relation has been obliterated due to the development of the chalcocite at the contact of the two (Plate XVI, Fig.4). However, there are some ores in which pyrite crystals come in direct contact with chalcopyrite with no chalcocite. Considering the original nature of pyrite and chalcopyrite, it is important to mark that the convexity of subhedral or subrounded pyrite is always towards chalcopyrite. At times, it is found that euhedral pyrite grains have been surrounded by chalcopyrite (Plate XVI, Fig.4). In a few other cases, some pyrite areas contain chalcopyrite with their concave outlines towards pyrite. The direct contacts of pyrite and chalcopyrite, the convexity of pyrite towards chalcopyrite as well as the concavity of chalcopyrite towards pyrite strongly suggest an automorphic outline relation of the two primary sulphides. Such textural relations between pyrite and chalcopyrite have been reported by a number of authors from similar other copper deposits. Schwartz and Park Jr. (1932, p.44-45) observed a similar texture in the oxidized copper ores of Campbell mine, Bisbee, Arizona, in which the disseminated crystals of pyrite occur in chalcopyrite areas. While describing the copper ores of Chambishi, Northern Rhodesia, Davidson (1931, p.450) says, "pyrite in all known cases is the earliest sulphide. It ... in many specimens is surrounded by chalcopyrite". Such mutual (automorphic) relations of one mineral with the other, has been applied in determining the age of pyrite, quartz and chalcopyrite (Bastin 1941, p.374-376).

Another very important texture developed due to the presence of veins of chalcopyrite in pyrite is the veined texture (Plate XVII, Fig.1). It is of course a rare occurrence in these primary sulphides of the Bageshwar deposits.

2. Pyrite and chalcocite

Some other interesting textural relationships exist between pyrite and chalcocite. Some of the pyrites have been replaced by chalcocite showing at times a typical "mesh structure" (Plate XVII, Fig.2). Nearly all stages of replacement of pyrite by chalcocite may be seen in these ores. Numerous irregular minute remnants of pyrite may easily be recognised in chalcocite areas which show the typical replacement texture of "relict type" (Plate XVII, Fig.3). Occasionally, these relict light yellow grains of pyrite in the sea of bluish white or white chalcocite appear like an "Ice Cake" (Plate XVII, Fig.4). Such a texture was described by Schwartz (1951, p.589) as the "Ice Cake" texture. In a few other cases where replacement is more or less complete, pseudomorphs of chalcocite after pyrite are formed.(Plate XVIII, Fig.3). Even in these cases, a careful examination sometimes reveals the presence of very minute pyrite remnants. Schwartz (1938, p.26-27; 1949,p.271), Jackson (1932, p.261) and many others have reported the replacement of pyrite by chalcocite with the development of similar textural relations.

3. Chalcopyrite-covellite-chalcocite

The chalcopyrite-covellite-chalcocite textural relation is probably the most important and interesting feature of these copper deposits. In nearly all cases, so far as the writer has observed, covellite envelopes chalcopyrite showing different stages of replacement (Plate XVIII, Fig.1). In the initial stage, the intergranular spaces in chalcopyrite are occupied by covellite in the form of rims around the chalcopyrite grains. In the subsequent stage, covellite advances further into the host mineral replacing it from the rim to the core region (Plate XVIII, Fig.1). This type of replacement is called the "rim replacement" (Edwards, 1960, p.171). Lindgren (1933, p.184) called such a texture "the centripetal replacement texture".

The replacement of covellite by chalcocite is indicated by the following observations:

1. Covellite has invariably been rimmed by chalcocite (Plate XVIII, Fig.1). A little chalcocite may occur in ores even without covellite, but there is no covellite without chalcocite association. In the initial stage of replacement, a rim of chalcocite develops around covellite.

2. The advanced stage of this replacement is indicated by a few unreplaced grains of covellite in the sea of chalcocite.

Many a time, chalcocite appears to replace chalcopyrite directly, but in such cases, a careful examination reveals the presence of a few intervening relict grains of covellite. Occasionally, chalcopyrite has veinlets of chalcocite.

The boundaries (margins) of covellite and/or chalcocite with chalcopyrite, and covellite with chalcocite were often found to be wavy and irregular (Plate XVIII, Fig.1). Covellite and chalcocite embay chalcopyrite, and similarly chalcocite embays covellite.

The chalcopyrite-covellite-chalcocite relations under low magnifications display, in general, a typical "mesh structure"(Plate XVIII, Fig. 2). Here, the reticulating veins of covellite and chalcocite criss cross areas of chalcopyrite in a mesh pattern. Depending upon the angles and patterns of intersection of these microveins, the unaltered chalcopyrite masses exhibit squared, rectangular or rhombic outline. Sometimes a similar mesh pattern is also developed in covellite which is intersected by veinlets of chalcocite. Such textures may be called "reticulating texture" (see Schwartz, 1951, p.590) or "mesh pattern" (see Bateman, 1950, p.40).

Mineral assemblages in oxidized zone

1. Chalcocite-cuprite-malachite relations

In majority of cases, cuprite is associated with chalcocite as a product of oxidation. Irregular veinlets of cuprite are more common in chalcocite. Such alteration of chalcocite is also pronounced along the boundaries which are formed of cuprite. Malachite was derived from both chalcocite (Plate XIX, Fig.2) and cuprite as a result of further oxidation. Malachite was also seen filling veins, open spaces and cavities in the ores (Plate XIX, Fig.1). It sometimes shows colloform banding with some gangue. In some highly oxidized ores malachite was veined by limonite (Plate XIX, Fig. 3).

2. Malachite-azurite

Azurite is rather a rare constituent of these ores. In one or two cases, veins of azurite were seen in malachite.

The author is of the opinion that the mineral assemblages and the textural relations of the oxidized copper ores, as described by either Schwartz (1938, 1949) or Jackson (1932) do not differ much from those observed in the Bageshwar deposits.

Mineral assemblages of the second phase of hydrothermal activity.

The second phase of hypogene mineralisation started with incomplete dolomitization, silicification followed by the deposition of the only lead sulphide, galena.

Galena-Jasperoid relations

Some interesting relationships between galena and jasperoid with which the former is exclusively associated (Plate IX, Figs. 3 and 4) are presented as follows:

a) Euhedral to subhedral quartz (jasperoid) shows automorphic relations with galena (Plate IX, Fig.4). The convexity of jasperoid boundaries are towards galena in almost all cases. No replacement relation was, however, seen.

b) Occasionally, jasperoid is completely enveloped by a mass of galena (Plate IX, Fig.4). In such cases, a difference in the grain size of jasperoid and galena is well-marked.

c) Another mode of occurrence of galena is in the form of veinlets occupying fracture spaces (Plate IX, Fig.3 and Plate XIX, Fig.4) in the silicified portions of carbonate country rock.

Interpretations of textures and microstructures

The study of the textures and the microstructures of the ore minerals provided significant informations regarding the sequence of formation of the ore minerals and their mode of formation. Most of the copper ore samples available from their surface or near surface occurrences reveal that hypogene ores of the first phase of hydrothermal activity were largely affected by oxidation and supergene sulphide enrichment. The deposit is now largely composed of the characteristic minerals of the zone of oxidation and supergene enrichment such as malachite, azurite, cuprite, limonite, chalcocite and covellite together with some proportions of pyrite and chalcopyrite of hypogene origin. An attempt has been made to determine the paragenetic sequence of the mineral deposits.

1. The nature of the contacts between pyrite and chalcopyrite indicates that either the former is older than the latter or they may have slightly overlapping age, pyrite preceeding chalcopyrite. This is corroborated by the fact that their contact lines are straight or wavy. The convexity of pyrite grains are always towards chalcopyrite. Similarly, in some pyrite areas, chalcopyrite grains show concave outlines towards the former. Another significant evidence in favour of this statement is the presence of veinlets of chalcopyrite in pyrite in a few ores. Again, there is no evidence of chalcopyrite replacing pyrite at any stage of mineralisation. It is necessary to mention here that excepting a few samples of ores in which this original contact between the two minerals is retained, pyrite and chalcopyrite are separated by chalcocite in a large number of such ores.

2. The occurrence of covellite as microveins in chalcopyrite is a strong evidence in favour of chalcopyrite preceeding covellite in age. It is further confirmed by the presence of covellite around chalcopyrite

in the form of rim and also by the fact that covellite have some unreplaced fragments of chalcopyrite in it.

3. Covellite appears to be older than chalcocite as the latter occasionally encloses small grains of the former. There are also some instances of rim replacement of covellite by chalcocite in the same manner as covellite replacing chalcopyrite. There are, however, some cases in which chalcocite appears to replace chalcopyrite directly.

4. The textural relations between pyrite and chalcocite as described in the earlier section of this chapter, clearly indicate that pyrite is older than chalcocite.

5. There are distinctly two generations of chalcocite in the ores under study. The earlier bluish white chalcocite is associated with pyrite. It has been veined by the second generation bluish grey chalcocite which is associated with chalcopyrite.

6. In most of the ores cuprite was found to be veining and replacing chalcocite along the vein walls. This indicates that cuprite is younger than chalcocite in age.

7. Malachite replaces both chalcocite and cuprite. Again, vugs in chalcocite are occupied by malachite and cuprite. The above features indicate that malachite is younger than cuprite with an overlapping age.

8. Azurite is of rare occurrence. In a few specimens azurite occurs in the form of veins in malachite. Azurite is thus definitely younger than the malachite.

9. The jaspereid shows in some cases automorphic outlines with galena which also occurs as vein, fracture and slip plane fillings. All these features thus indicate that the deposition of galena took place after silicification of the dolomitic limestones. The difference in the grain size of jaspereid and galena may be taken as a significant criterion of age relation between the two(Bastin,1950,p.52). Jasperoid being fine-grained preceeds the coarsely crystallise galena following the same principles as recorded by Bastin (1951) for determining the paragenesis of quartz phenocrysts and their matrix in a porphyry. Further, the precedence in age of jasperoid over galena has been confirmed from the thin section study of lead bearing rocks.

A similar evidence was recorded by Bastin(1951)for the earlier appearance of jasperoids associated with the lead-zinc deposits of Tri State district,U.S.A. Hence, in the present case, it may safely be concluded that galena was deposited subsequent to the silicification of the country rocks.

<u>Paragenesis</u> - The entire sequence of mineral formation may,therefore,fall into an earlier hydrothermal and a later supergene stage.The hydrothermal stage is subdivided into two sub-stages which correspond to two phases of mineralising events viz., the earlier of copper-iron sulphides and the later of lead sulphide.

Chiefly based on the above discussion and interpretation, the paragenesis of the copper and lead minerals and also of their gangue associations are summarised in the following tables. The relative time of appearance of associated gangue minerals are taken from the chapter on wall rock alteration.

TABLE - VII

<u>Paragenesis of the hypogene ore and gangue minerals</u>

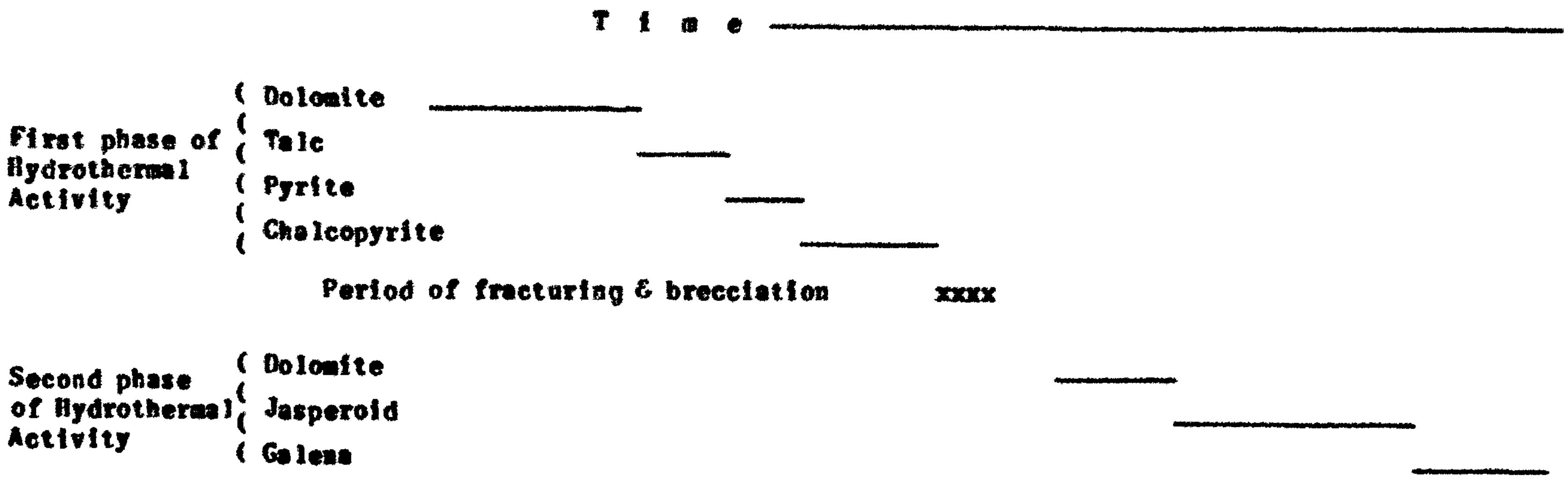
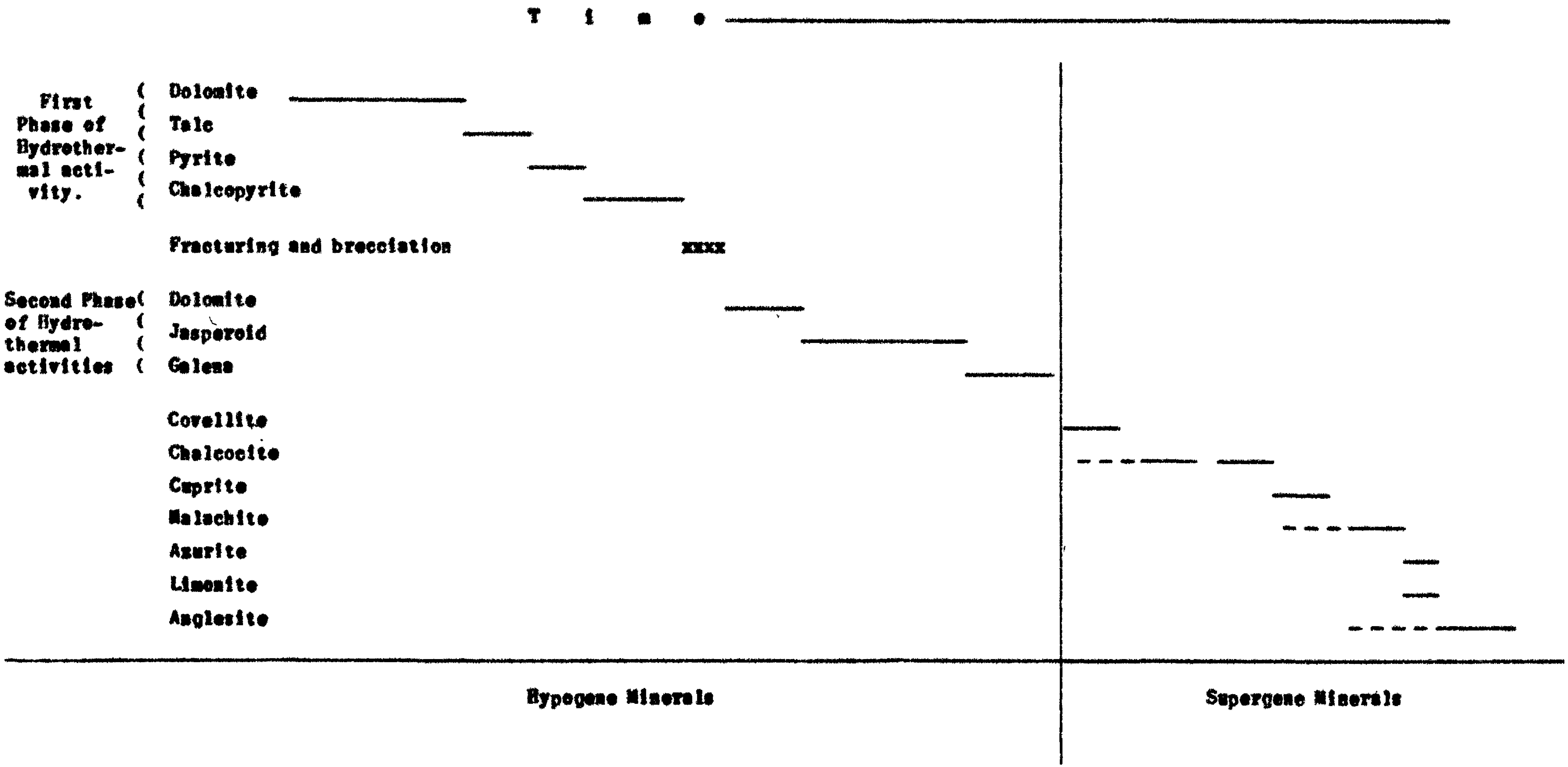


TABLE - VIII

Complete Paragenesis of the Ores and Gangue Minerals Associated with the Copper and Lead Deposits of the Bageshwar Area.



Chapter - VII

GENESIS OF THE COPPER & LEAD DEPOSITS

General Statement

The deposits were studied in a near surface conditions as no mining is in operation. Therefore, the present study is confined mainly to the zone of supergene sulphide enrichment and oxidation. The only hypogene ore-minerals associated with ore-deposits are pyrite, chalcopyrite and galena. Pyrite and chalcopyrite together with several other minerals of the zone of sulphide enrichment and oxidation occur in the completely dolomitized halos of Balaldev, Ghirauli and Tamkhani. Talc-schist is also a host for the copper ores in parts of Balaldev ridge. The lead ore, galena, occurs at Purshishkhani, Short, Chhenapani and south of Balaldev in the form of vein and fracture filling, and also as disseminations in silicified dolomitic limestone.

Very few of the earlier workers have described the geology of the Sarju Valley in Bageshwar in general and of the copper-lead deposits in particular. Subramanyam and Jain (1961)are of the view that the deposits indicate a low temperature phenomenon without any development of calcium or magnesium silicates from the impure dolomites. Nautiyal (1962) suggested that the copper deposits of Almora and Pithoragarh districts were of hydrothermal origin and the source of the solution were the basic sills. An epithermal origin has been suggested for the lead deposits of Chhanapani, Almora, by Rasul and Sharma (1963). It is important to mention here that none of the earlier workers made serious attempts to undertake the problems of genesis of these deposits. The present author had the opportunity to undertake a detailed study of the mineralogy and textures of ores, the structure of the host rocks and their control on ore localization, the nature of wall rock alteration and also zoning in the ore deposits. The author has been able to conclude that the copper-lead deposits of Bageshwar are of hydrothermal origin and that the deposition took place in two phases of hydrothermal activity, each phase representing a zone. The ore minerals of the first and second phases of hypogene mineralisation have been affected by subsequent supergenes sulphide enrichment and oxidation.

In accordance with the above observations the Bageshwar copper-lead deposits may be classified into two genetic types, viz., 1) hypogene ores deposited from hydrothermal solutions, and 2) supergene sulphide and oxidized ores - formed by descending meteoric waters and subsequent oxidation.

1. Mineralization by hydrothermal solutions

The original composition and texture of ores have considerably been altered, although associated with the present supergene ores. There are a few ore minerals which may be called hypogene. The hypogene minerals are pyrite, chalcopyrite and galena. They were found to occur mainly in the Shishkhani-Chhanapani-Balaldev belt of copper and lead. Nautiyal (1962, p.357) suggested that the only primary mineral present in Bageshwar copper deposits is, chalcopyrite. Rasul and Sharma (1963) observed galena as the only primary mineral in Bageshwar lead deposits.

The present author's argument in favour of hypogene origin for chalcopyrite and pyrite from the copper, and galena from the lead deposits of Bageshwar are based on the following observations:

i) The replacement of the gangues such as talc and dolomite by pyrite and chalcopyrite is a strong evidence in favour of a hypogene pyrite and chalcopyrite (see Schwartz, 1932, p. 545).

ii) The typical automorphic outline relation between pyrite and massive chalcopyrite suggests successive deposition under hypogene conditions. Ridge (1936, p. 302) recorded similar textural relations in the hypogene pyrite in the Tri-State Zinc-lead deposits, U.S.A. A similar automorphic outline relation was observed by Tuck (1931) in the hypogene sphalerite-galena ores of Geneva Lake, Ontario. Bastin (1941, p. 375) observed automorphic outline relation between hypogene pyrite and quartz. Later, Bastin (1951, p.655) described automorphic relations between the hypogene sphalerite and jasperoid of the Tri-State districts, U.S.A.

iii) The pyrite-chalcopyrite relationships never display either 'mesh' or centripetal (peripheral) replacement texture which is characteristically of supergene origin.

iv) Occasionally, one or two edges of the pyrite crystals have straight contacts with chalcopyrite. This tendency of mutual boundary relation between pyrite and chalcopyrite is an indication of their deposition under the same hypogene conditions (see Schwartz, 1932, p. 537).

v) The hypogene quartz (jasperoid) shows automorphic outlines against galena indicating that galena is also a hypogene mineral.

Evidence of hydrothermal origin

In the following pages an attempt is made to review the evidence in favour of hydrothermal origin of the Bageshwar sulphide deposits.

a) Wall rock alteration - Alteration of wall rock is the most important and definite characteristic of hydrothermal (epigenetic) ore deposits. Hydrothermal alteration of the carbonate rocks is a prominent feature that has been discussed at considerable length in the earlier chapters. The genetic processes involved in the alteration of the host rock were reported to be dolomitization, silicification and the formation of talc. Dolomitization followed by ore deposition, is a fairly common sequence reported in a number of localities throughout the world (see Hewett 1928 and others). The unique feature in the present case is that dolomitization preceded the formation of talc and both the processes preceded the deposition of sulphides of the first phase.

Then, considering the second phase of hydrothermal activity, the paragenetic sequence of the wall rock alteration and ore deposition is dolomitization, silicification, lead deposition. The above sequence has also been reported in a number of hydrothermal ore deposits (see Lovering 1949 and also personal communication 1967). The association of the areas of intense silicification and sulphide mineralization in parts of Kherzet Yousef and Djebel Guster (both in Algeria, Mississippi Valley Type lead-zinc deposits) has recently been taken as a strong evidence of mineralization by hydrothermal solutions (see Dubovnik, 1967, p.117-119).

b) Ground preparation for sulphide deposition - In the earlier discussion (p. 81) it has been pointed out that there is ample evidence to show an increase in porosity, permeability and the intensity of fracturing through dolomitization. In other words, the altered rocks have been made more favourable and receptive loci for the deposition of sulphides. Dolomitization thus, was an important pre-metallizing process involved in the "ground preparation" for deposition of the sulphides. Park Jr. and MacDiarmid (1964, p.58) have pointed out that pre-metallizing "ground preparation" processes are the most characteristic features of the epigenetic (hydrothermal) deposits.

According to Park Jr. and MacDiarmid (1964, pp.58 and 141) silicification is the most common pre-metallizing process of ground preparation, e.g., at East Tintic district, Utah (Lovering, 1949), Tri-State district, U.S.A. (Bastin, 1951), etc. Park Jr. and MacDiarmid (1964, p.144) state that the process of silicification makes the soft impermeable and unfavourable rocks more competent and more receptive to the introduction of fluids and the ore deposition.

c) The nature of gangue minerals - The normal gangue minerals associated with low temperature hydrothermal ore deposits in the carbonate rocks are quartz, dolomite, etc. (see Park Jr. and MacDiarmid, 1964, p. 146, 330-331 ; Ohle, 1959, p.777; Lindgren, 1933, p.446; etc). Also talc was found in the ore deposits but its occurrence is rare. (see Lindgren, 1933, p.392) and Bateman (1959, p.296). An intimate association of the above said gangue minerals with the sulphides in the Bageshwar deposits further suggest a low temperature hydrothermal origin.

d) Paragenesis and other mineral evidence - For the mesothermal deposits, Lindgren (1933, p.544) gave the following paragenetic sequence in general, and stated,"the sulphides usually form in the following order, exceptions from this sequence being rare". The sequence determined by the author for copper and lead deposits of Bageshwar, is also given for comparison with Lindgren's sequence.

Paragenesis of the Mesothermal deposits (after Lindgren)		Paragenesis of the copper-lead deposits of Bageshwar
Early	Pyrite	Pyrite
	Arsenopyrite	
	Co-Ni arsenides	
	Pyrrhotite	
	Sphalerite	
	Enargite	
	Tennantite	
	Tetrahedrite	
	Bornite	
	Chalcopyrite	Chalcopyrite
	Galena	Galena
	Argentite	
	Gold	
Late	Sulphosalts of Au and Ag	

From the above table, it is evident that a large number of sulphides are missing from the Bageshwar deposits, but it is important to note that the relative positions of pyrite, chalcopyrite and galena is the same as described in the Lindgren's sequence. The deposits, however, are not of the mesothermal type. To explain these discrepancies, the author feels he cannot do better than to quote Lindgren (1936, see Brown, 1950, p.19), who says, "... the interesting fact soon becomes apparent that practically the same paragenesis holds for contact-metamorphic, hypothermal, mesothermal and epithermal deposits. Some minerals or classes of minerals may be absent but, as a rule, the relative position is the same".

In the oxidized and supergenetically enriched copper ores of Bageshwar, the sequence of primary sulphides is pyrite and chalcopyrite. This is a fairly common hypogene sequence described from a number of copper deposits of hydrothermal origin. Schwartz (1938, p.25) described pyrite, chalcopyrite and "possibly bornite" as the only primary sulphides in the oxidized ores of U.V. Extension Mines, U.S.A. Jackson (1932, p.258) described a sequence of pyrite, chalcopyrite and linnaeite for the hydrothermal deposits of N'Changa, Northern Rhodesia, Africa. Further, Schwartz (1947, p.346) described a similar paragenetic sequence for a number of porphyry copper deposits of well accepted hydrothermal origin. Lindgren (1933, p.498) has mentioned a pyrite-chalcopyrite sequence in some epithermal base metal deposits. The author strongly feels that the paragenetic sequence of hypogene sulphides in the copper and lead deposits of Bageshwar is a normal hydrothermal sequence.

The mineralization of copper and lead in two distinct phases is an important observation which has been discussed elaborately in the Chapter V. According to Lindgren (1928, p.521-524 and 1933, p.447-450) successive phases of mineralization is a characteristic feature of epithermal deposits. He (1933, pp. 447-448) stated, "As earlier gangue mineral such as calcite or barite, may be wholly wiped out and replaced by a new gangue of quartz and adularia. This alteration has nothing to do with surface waters ...". Further, Ridge (1936, p.306) described two stages of mineralization in the Tri-State district, U.S.A., as an evidence of hydrothermal (ascending) solution rather than the meteoric waters. He further states that there is nothing in the mechanism provided by the artesian hypothesis to suggest that fracturing should bring with it a change in the character of the ore bearing solution.

The author, finally feels that the evidence of two phases of mineralization at Bageshwar may be taken as a definite criterion of ore deposition by hydrothermal solutions under epithermal conditions.

The occurrence of chalcopyrite as Ridge (1936, p. 307) says, is itself an evidence of ore deposition by hydrothermal solutions. He says, "it is well known principle that a double salt, such as chalcopyrite, when dissolved in ground water, reprecipitates not as a double salt but as single one". Chalcopyrite and sphalerite are found with magmatic solution deposits everywhere and this group of minerals, as a whole, is typical of magmatic water deposition (see Tarr, 1936, p.863).

e) Temperatures of deposition - Mineragraphic work done so far has not been specifically directed towards determining the temperature of deposition and the geothermometric investigation remains to be done with this specific purpose in view. Some of the lines of evidences available are discussed below:

i) In the mineralized zones, the absence of wollastonite indicates that the temperature had not reached upto 600°C, if the fluid pressure was supposed to be 1,000 bars (see Turner and Verhoogen, 1962, p.519).

ii) The absence of periclase in the altered wall rock indicates that the temperature in contact zones had not reached upto 400°C, whatever the fluid pressure might have been (see Turner and Verhoogen, 1962, p.519).

iii) No development of tremolite, forsterite and diopside from silica and dolomite has been observed. This feature indicates that the temperatures have not reached 450°C (see Ingerson, 1955, p.378; Fisher, 1960, p.103; Stringhom, 1952, p.662).

iv) The formation of talc in the copper deposits is a definite indicator of hydrothermal activity at low temperature. "It results from mild hydrothermal metamorphism, perhaps aided by simple dynamic metamorphism..."

(Bateman, 1959, p.296). He further states, "Talc is always late in mineral sequence. It is formed largely from other minerals that in turn represent alteration product of original minerals". A similar situation appears to exist in the present case. The formation of talc proceeded the dolomitization of limestone. The following chemical equation represents the formation of talc from dolomite (see Winkler, 1965, p.19):

3 Dolomite + 4 quartz + 1 H_2O = 1 talc + 3 calcite + 3 CO_2.

$$3\ CaMg\ (CO_3)_2 + 4\ SiO_2 + 1\ H_2O = Mg_3Si_4O_{10}\ (OH)_2 + 3\ CaCO_3 + 3CO_2$$

Tilley (1948, see Deer et al. 1962, p.128) suggests that talc is formed in the earliest stage of thermal metamorphism of dolomites. Turner and Verhoogen (1962, p.511) described the formation of talc in the lowest grade of contact metamorphism (i.e., Albite-Epidote-Hornfels facies). While describing the temperatures of the formation of some common hydrothermal minerals, Stringham (1952, p.662) mentioned that talc is formed at a temperature of about 175°C. In view of the above statements, the author finds some justification to believe that the talc is a product of thermal metamorphism due to the invasion of the hydrothermal solutions which at an earlier stage had dolomitized the limestone country at Bageshwar.

v) The epigenetic origin of the dolomite associated with the copper deposits of Bageshwar has already been discussed in the earlier chapters. Lovering (1958, p.700) after a detailed geothermometric studies on the dolomites arrived at the conclusion that the early hydrothermal dolomitization at Gilman district, U.S.A., reached a *maximum temperature of 300°C, but before dolomitization ended, the* temperature had declined to slightly above 200°C. Similarly, according to Stringham (1952, p.662), the formation of hydrothermal carbonate minerals takes place at temperature of about 250°C. Following Stringham (1952, p.662) and Lovering (1958), the author strongly suggests that the hydrothermal dolomitization of the carbonate rocks of Bageshwar probably took place at about 225°C and this declined to about 175°C when talc was formed in the dolomites.

vi) The complete absence of any exsolution texture in these ores, rules out their formation under high temperature conditions. There are instances of epithermal pyrite and chalcopyrite deposits (see Lindgren 1933, p.498). Deposition of the ores at low temperature is supported by the fact that high temperature minerals like pyrrhotite, arsenopyrite, stannite, etc. are not associated with the ores. The minerals like pyrite and chalcopyrite are of course, not "typomorphic" minerals of low temperature deposits. But Ramdhour (1966, p.208-209) mentioned that pyrite and chalcopyrite might be sometimes "transcurrent minerals", i.e., they are formed in deposits ranging from high to low temperature. Further, in the low temperature assemblage of lead-zinc deposits, Ramdhour (p.238) included sphalerite, galena, pyrite, chalcopyrite, tetrahedrite, etc.

Thus, considering the nature of wall rock alteration, the mode of occurrence and mineralogy of ores, a lower epithermal zone of hydrothermal deposits, appears more acceptable for the copper deposits of Bageshwar.

Field and other evidence show that the first phase of mineralisation was followed by a period of brecciation and fracturing. Then, the second phase of hydrothermal activity started with incomplete (or mild) dolomitisation, intense silification and finally ended with the deposition of galena. From the gangue and ore assemblage, it is evident that this phase of mineralisation took place at a lower temperature than the first phase. Silicification of limestones is a characteristic features of epithermal deposits (see Lindgren, 1933, p.508). While summarising the epithermal deposits in limestones, Lindgren (1933, p.508) pointed out that limestones under epithermal conditions would be silicified and not silicated.

Considering the temperatures established for the first phase of hydrothermal mineralization, the mineralogy of the hypogene sulphides in the second phase of hydrothermal activity and following Ingerson (1955), the author estimates a temperature of about 100° to 150°C for the replacement of limestone/dolomite by jasperoid in the lead deposits of Bageshwar.

From the above observations, it appears that second phase of ore mineralisation represents the upper zone of epithermal type of deposits.

f) Types and nature of ore-zoning - Zoning with respect to the postulated or proved magmatic source is a generally accepted criterion of hydrothermal ore deposits. The author recognised two types of zoning in the Bageshwar deposits.

i) The district zoning

ii) Zonal distribution pattern of Ca/Mg, SiO_2, CO_2 around copper deposits.

The distribution of dolomite-talc-pyrite-chalcopyrite assemblage in the central zones and the dolomite-jaspereid-galena in the peripheral zones, suggests the district zoning. The central zones probably represent the lower epithermal zone and the peripheral zones represent the upper limits of epithermal zone. Even in the most controversial Mississippi Valley Type Deposits, such central and peripheral distribution of metallic minerals has been taken as an evidence of hydrothermal origin. Heyl (1967, p.28) described, "the low temperature minerals in the peripheral lead-zinc ores compared with those of the complex silver-lead deposits towards the heart of the district, suggest their formation as low temperature fringe end members of the central silver-lead districts". In the hydrothermal chalcopyrite, lead, zinc, barite, fluorite deposits of the English Pennines, Dunham (1967, p.203-204) described five zones with the pyrrhotite-chalcopyrite in the central zone and barite-witherite in the outer most peripheral zone.

The zonal distribution of Ca/Mg ratio, CO_2, SiO_2 contents around the copper deposits of Balaldev ridge, Bageshwar, is reflected by a decrease in the Ca/Mg and SiO_2/CO_2 ratios towards the ore bodies. The variations thus, distinctly suggest the stages of hydrothermal dolomitization and also the diminishing activity of the hydrothermal solutions. Riley (1936, p.172-181) studied some other types of variations in the altered and unaltered host rocks associated with the lead-silver deposits of Sierra Majada, Mexico.

g) <u>Simplicity of mineralogy</u> - From the mineragraphic studies, it is evident that the mineralogy of hypogene minerals in the Bageshwar deposits, is exceptionally simple. The formation of deposits by long distance travelled hydrothermal solutions is probably an explanation for the simple hypogene mineralogy. Many of the well known epithermal deposits of quick silver and antimony are simple in hypogene mineralogy. In the genetic discussions of the quick silver deposits of Terlingua region, Texas, U.S.A., Ross (1941, p.138) points, "The solutions were dilute and, even if they ever contained other heavy metals, most of these had been dropped before the solutions reached the shallow depths at which precipitation took place". Similarly, Ohle (1959) described simple ore mineralogy as a characteristic feature of the Mississippi Valley Type Deposits. Ohle (1951, 1959) is an strong supporter of a hydrothermal origin for the Mississippi Valley Type Deposits.

While discussing the genesis of the lead-zinc deposits Dubovnik (1967, p.119) explained that the simple mineralogy reflects long distance between ore deposits and the source of ore forming solutions.

(h) Structural controls on ore-localization

The mineralisation of copper is confined to more fractured and porous zones of dolomite. It reflects the fact that the pore and fracture spaces played an important role in the localization of pyrite and chalcopyrite. Replacement, however, was also observed to a minor extent wherein talc was replaced by the sulphides. Slip planes, fracture planes and veins are believed to be the chief controls of galena localization. All the above features are again strong evidence of an epigenetic ore deposit (see also Sullivan 1957 p.20-22 ; Bateman 1959) and others.

Supergene sulphide enrichment and oxidation

The hypogene deposits of the first and second periods have been greatly modified by supergene sulphide enrichment and oxidation. The supergene replacements and alterations are more prominent and well marked in the copper deposits than in the lead. However, lead deposits also show some features of oxidation. Characteristic minerals of the zones of oxidation and enrichment are malachite, azurite, cuprite, chalcocite, covellite, anglesite and limonite.

Covellite and chalcocite are the sulphides which are known to be hypogene as well as supergene in origin [Fischer (1936), Bateman (1930; 1959)]. It is, therefore, necessary to discuss here the nature of covellite and chalcocite. The following facts indicate a supergene origin for the covellite and chalcocite reported from Bageshwar.

1. The chalcopyrite-covellite-chalcocite relations which display a "rim replacement" and "mesh pattern" are indicative of the supergene nature of both chalcocite and covellite.

2. In a few polished sections, a similar 'mesh pattern' has been recorded in the pyrite areas which have been intersected by reticulating veinlets of chalcocite.

3. The pseudomorph of chalcocite after pyrite with some remnants of pyrite is also a result of supergene replacement. While describing the supergene copper sulphides, Lindgren (1933, p.834) says, "Pyrite may be converted to sooty or massive chalcocite with only a few residual grains of the original mineral". Similarly Schwartz (1938, p.26) while

describing the supergene chalcocite of the United Verde Extension Mines, U.S.A. reported the pseudomorphous replacement of pyrite by chalcocite.

4. In about 80 per cent cases, the pyrite-chalcopyrite contact is marked by chalcocite. This type of replacement wherein the replacement is related to the contact of two minerals, is a characteristic feature of supergene replacement.

The above discussions thus, indicate that the covellite as well as the chalcocite are of supergene origin.

The replacement of chalcopyrite by covellite, under supergene conditions takes place as illustrated in the following chemical equation:

i) $CuFeS_2 + CuSO_4 = 2\,CuS + FeSO_4$

The supergene replacement of covellite (or chalcopyrite) by chalcocite may be expressed by the following chemical equations:

ii) $5CuS + 3CuSO_4 + 4H_2O = 4Cu_2S + 4H_2SO_4$

iii) $5CuFeS_2 + 11CuSO_4 + 8H_2O = 8Cu_2S + 5FeSO_4 + 8H_2SO_4$

Similarly, the replacement of pyrite by chalcocite under supergene conditions is expressed as:

iv) $5FeS_2 + 14CuSO_4 + 12H_2O = 7Cu_2S + 5FeSO_4 + 12\,H_2SO_4$

It appears that supergene enrichment of both pyrite and chalcopyrite was facilitated by the more permeable dolomitized zones which were the easy channels for the movement of descending meteoric waters. A reverse case was observed by Jackson (1932, p.259) where the replacement of pyrite by chalcocite was uncommon due to the intense silicification of the host rock.

Oxidation

Cuprite, malachite and azurite are commonly regarded as the copper ores of oxidized zone. In the Bageshwar copper deposits the boundary between supergene sulphide zone and the oxidized zone is not at all defined. A porous cupritic and malachitic zone was, however, located as the outcroping surface in parts of the Balaidev and also Ghiraull copper deposits. An attempt is made here to describe the formation of the minerals of oxidized zone.

The replacement of chalcocite by cuprite under oxidising condition may be represented by the following chemical equation:

$$Cu_2S + 2O_2 + H_2O = Cu_2O + H_2SO_4$$

Similarly, the replacement of cuprite and chalcocite by malachite may be expressed as follows:

$$Cu_2O + H_2CO_3 + O = CuCO_3 \left[Cu\ (OH)_2 \right]$$

$$CuS + CO_2 + 2H_2O + 5O = CuCO_3\ \ Cu(OH)_2 + H_2SO_4.$$

Finally, the replacement of malachite by azurite might have taken place according to the following equation:

$$3 \left[CuCO_3\ \ Cu(OH)_2 \right] + CO_2 = 2 \left[2\ (CuCO_3\ \ Cu(OH)_2) \right] + H_2O$$

The oxidation of galena is marked by the development of anglesite as shown in the equation:

$$PbS + 2O_2 = PbSO_4$$

Probable source of hydrothermal solutions

The fundamental question as to the source of the metals in the Bageshwar deposits is probably an enigma.

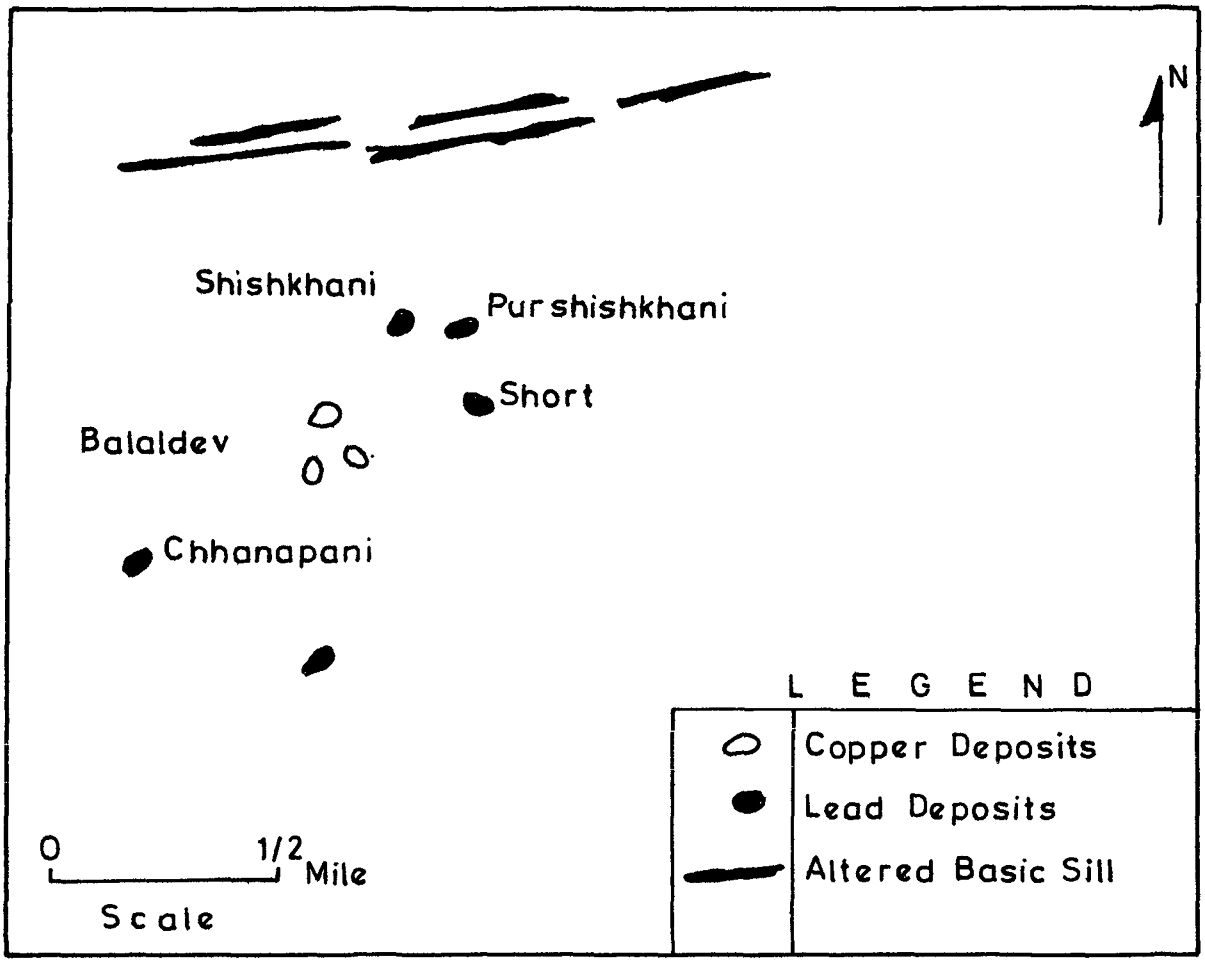


FIG. 12 FIELD RELATION OF THE ALTERED BASIC SILLS AND COPPER LEAD DEPOSITS; SHISHKHANI-CHHANAPANI BALALDEV BELT

Nautiyal (1962) regarded the basic sills to be the source of hydrothermal solutions responsible for the deposition of the base metals at Bageshwar and elsewhere in the region only because of the occurrence of basic sills in the vicinity of the deposits located at Shishkhani, Chhanapani, Balaldev and Dewaldhar. But Subramanyam and Jain (1961) who also reported the occurrence of highly altered basic sills and dykes in the vicinity of the mineralised belt, are of the view that the basic rocks had no relationship with the ore deposits. None of the above authors gave any evidence in support of their views.

The present author also strongly feels that the altered basic sills are not the source of hydrothermal solutions in this region. The following evidence support the author's statement:

1. The distribution of the copper and lead deposits in Shishkhani-Chhanapani-Balaldev region, and its relation to the altered basic sills is given in Fig. 12.

Fig. 12 clearly suggests that the altered basic sills could not have any genetic relationship with the ore deposits. The comparatively low temperature zone (or the peripheral zone) of lead mineralisation (Pur Shishkhani and Short) appears to be closer to the basic sills. The comparatively high temperature zones of pyrite and chalcopyrite (i.e., the central zone) is farther away from the sills. If the basic sills were the source, then they should have been closer to the central copper zone and farther away from the peripheral lead zone.

Thus, the zonal pattern of ore deposits and their areal relation with the basic sills do not support the idea that the sills have anything to do with the mineralization.

2. The basic sills have been encountered throughout the region particularly in the quartzite zones. If the sills were the source of the metals, then there ought to have been some mineralization in the phyllites or even in the quartzites as well. The author did not find any trace of copper or lead ores in either the quartzites or phyllites both of which overlie the carbonates having some ores.

3. According to Gansser (1959, see Valdiya, 1965, p.534), these basic sills are "ophiolites", i.e., they were emplaced more or less contemporaneously with sedimentation. In the adjacent district of Pithoragarh, Valdiya (1965, p.538) observed similar altered basic sills at the contact of quartzites and the crystalline group on one hand and at the contact of quartzite and carbonate rocks on the other

The present author finds some justification in accepting this view of Gansser (1959) and Valdiya (1965) that the basic sills were emplaced more or less contemporaneously with sedimentation. The contacts of the basic sills and the meta-sedimentary rocks are remarkably sharp. Another important feature is that the basic sills from the regions where there are no mineralisation are typically altered into epidiorites, mostly dark green in colour. The basic sills that have been encountered in the Shishkhani-Channepani-Baleldev region are dull yellowish brown and red with some soapy feel. This indicates the fact that the basic sills in the mineralised area themselves have undergone some alteration. Thin section study of these rocks however, failed to throw any light on the processes of alteration involved.

The above evidence thus, strongly indicates that at least the basic sills did not supply the mineralizing solutions. The absence of any other visible igneous rocks, which may be regarded as the source of hydrothermal solutions precipitates an enigma which the author leaves to future investigators. However, the author wishes to suggest some probabilities in this regard.

Probable source - The ore bearing fluids might have ascended from some unknown deep seated magmatic source and there were some direct channelways (major faults) between the pluton (or intrusive) and the near surface rocks in which the ores were deposited. It is also postulated that the deep seated plutons might have contributed necessary heat and some of the elements of the deposits.

The above statement of the present author, probably gets some support from Wadia (1966, p.90), who says, "Later investigators have proved that much of this gneiss, as is the case with that of the Himalayas as a whole, is not of Archaean in age, but is of intrusive origin and has invaded rocks of various ages at a number of different geological periods".

While describing the low temperature hydrothermal deposits of chalcopyrite, pyrite, stibnite and uraninite in the adjacent district of Chamoli Himalayas, Dar (1964, p.116) made the following observations:

> "Mineralising solutions here appear to have been derived from deep seated parts of the Central Himalayan Gneiss seen about 40 to 50miles north of this area".

In the Mississippi Valley Type Deposits, a number of eminent scientists have proposed the existance of such deep seated unknown plutons to explain the origin of the hydrothermal solutions. Lindgren

(1933, p.508-509) stated that fissuring and mineralization was caused by and followed the dome-like uplifts and that these were due to deep-seated intrusions not yet exposed by erosion. The metals in the deposits would then have been derived from the ascending emanations of these deep-seated intrusives. In considering the origin of the Mississippi Valley Type Deposits, Ohle (1959,p.786) has also supported the view that the ores were derived from some unknown deep seated magmatic source. While discussing the origin of the Central Kentucky Mineral deposits, Jolly and Heyl (1964, p.620) advocated that a deep seated pluton could have provided a convenient heat source and some of the elements of the deposit. Recently Heyl (1967, p.26-30) discussed certain aspects of the genesis of stratiform lead-zinc-barite-fluorite deposits of U.S.A. and stated that such deep seated intrusives could have provided the heat and abundant volatiles needed to start the connate brines in circulation.

Following Dar (1964), Wadia (1966), the bulk of literature available on the Mississippi Valley Type Deposits and his own observations in the twin districts of Almora and Pithoragarh Himalayas, the author strongly suggests that the mineralizing solutions were derived from the deeper parts of the Central Himalayan Gneisses which were also intruded by granites at different periods of Himalayan orogeny. The movement of solutions was along deep seated major faults. There are some five localities in Bageshwar wherefrom copper was reported. In the author's opinion, this distribution of the copper ores indicates five close centres of mineralisation which were collectively related to some unknown deep faults existing between the intrusives and the ore bearing rocks. Then, it appears that the mineralogy of the deposits lying in the south and north of Bageshwar may also change according to distance of the deposits from the Central Gneisses. The most unfortunate thing is that with the exception of Shishkhani-Chhanspani-Balaidev copper-lead belt, none of the deposits contain any primary mineral. Only in a few cases some chalcocite, cuprite and malachite may be seen in the oxidized areas. According to the hypothesis, put forward by the present author, it is logical to expect high temperature deposits in the vicinity of the Central Gneisses and the low temperature deposits further to the south of the Gneisses. This has been supported by the following facts:

1. At Askot, a locality much closer to the Central Gneisses, a high temperature mineral assemblage of pyrite, arsenopyrite, chalcopyrite and galena has been reported in the crystalline schists and gneisses (see Jhingran, 1965, p.159).

2. The low temperature hydrothermal sulphide deposits were reported in Chamoli region about 40 to 50 miles south of the crystalline gneisses (see Dar, 1964).

3. In the carbonate rocks of the inner sedimentary zones, which lie 25 to 40 miles south of the Central Gneisses, low temperature hydrothermal sulphide deposits have been noticed throughout the region, e.g., at Almora, Pithoragarh, Garhwal, Tehri, etc.

Type of deposit

The author finds some justification in classifying the deposits to be of Epithermal Type (Lindgren's classification, 1933, p.445). Certain features appear to be characteristic of the Mississippi Valley Type Deposits, but considering the presence of hydrothermal talc, the successive phases of mineralization, the intense dolomitization and sillicification; and the absence of any barite, fluorite, sphalerite, the author is more inclined to classify these deposits as epithermal.

Finally, the author feels that the origin of the copper and lead deposits of Bageshwar constitutes a complex problem which will require many additional observations before a satisfactory solution can be reached.

SUMMARY AND CONCLUSION

The investigation was mainly concerned with the nature and mode of occurrence, mineralogy, structural and lithological controls and the probable origin of the copper and lead deposits, encountered in several old workings and spread over an area of about 55 sq. miles around Bageshwar in the hilly Almora district of Kumaon Himalayas, Uttar Pradesh State, India. Summary and conclusions of the work are presented as follows:

1. Most of the previous workers, who studied the geology of the present area and some of its adjacent regions in the Kumaon Himalayas, were chiefly concerned with the stratigraphy and sedimentation on a regional scale. Earlier publications show that the geology, structure and the nature and origin of the associated base metal deposits of the area were not of much concern to them.

In order to have a better understanding of the stratigraphic and structural set-up of the rock formations in which copper and lead ores occur, the author had constructed a geological map covering an area of about 55 sq. miles around Bageshwar. Most of the important old workings in the area are found either on the north or south of Bageshwar.

2. The rock formations, which are predominant in the area may broadly be classified into the following three types:

a) Baijnath crystallines - gneisses and schists.

b) Bageshwar quartzites - Predominantly orthoquartzites.

c) Calc-zones of Bageshwar = (Dolomitic limestones
(Slates

The calc-zones of Bageshwar were described sectorwise viz., (i)North Bageshwar calc-zone and (ii) South Bageshwar calc-zone. The north Bageshwar calc-zone appears to be the westward continuation of the calc-zone of Tejam, and the south Bageshwar calc-zone, the westward continuation of the calc-zone of Pithoragarh. The calc-zones, both in the south and north of Bageshwar, are essentially made up of a conformable sequence of slates below and carbonate rocks above. There are several varieties of slates and carbonate rocks. Algal stromatolites (genus Collenia) are occasionally associated with the limestones in the calc-zones. The varieties of carbonate rocks, which hosted the two base metals viz., copper and lead, are dolomites, talc-dolomite rocks and silicified dolomitic limestones of the Shishkhani-Chhanapani-Balaldev calc-zone belt, etc. The author has enough evidence to support the view of Gansser (1964) that the calc-zones of Bageshwar and the Deoban limestones of Chakrata area are homotaxial and therefore, belong to the Upper Precambrian to Lower Cambrian age.

The Bageshwar quartzites are the westward continuation of the Berinag quartzites (Ordovician age) and they conformably overlie the calc-zone rocks of Bageshwar.

The Baijnath crystallines (Precambrian) were thrusted over the Bageshwar quartzites, perhaps sometime during the period of Himalayan orogeny (Tertiary). This is known as the Baijnath thrust. All the formations below the thrust are right-side-up.

Based on field study and the geological map, constructed by the author, the sequence of rock formations of the area has been established as follows:

Baijnath Crystallines	(5. Augen gneisses, schists and mylonites.
——— Baijnath Thrust ———	
Bageshwar Quartzites	(4. Orthoquartzites with intercalated phyllites and altered basic sills.
Calc zones of Bageshwar	(3. Dolomites, talc dolomite-rock, talc schist, silicified dolomitic limestone with copper and lead ores.
	(2. Algal stromatolitic limestones with thinly bedded calcareous phyllites at the base.
	(1. Slates
	? (Base Unknown)

3. Structurally, the area under present investigation, forms a broad north-westerly plunging refolded syncline, introduced here as the Bageshwar syncline. The trends of other folds within the syncline both in the north as well as south of Bageshwar are also NW-SE, and their plunges vary from 20° to 45° northwest. Among the refolded folds more conspicuous ones are described as the Kathathbara syncline, Gomati anticline, Chhana anticline, Ghirauli syncline, Kaphlikhet syncline and the Sarju Valley anticline, which were named according to their geographical locations. The area was also structurally disturbed by a major thrust fault and several other faults. Nearly the first six miles of the south-eastern

part of the thrust falls within the area under review. Most of the faults are either parallel to the general trend of the folds or cross them from NE to SW. Three sets of systematic joints namely, striking NW-SE, NE-SW, and N-S, frequently occur in the various rock types of the area.

Among the various primary or non-diastrophic structures recorded from the metasedimentary rocks below the Baijnath thrust, mention may be made of planer bedding, cross bedding, ripple marks and graded bedding. These structures not only indicate that the origin of slates, limestones and the quartzites is sedimentary but also that their order of superposition is normal in the area concerned.

4. A detailed petro-mineralogic study of the limestones, quartzites and the basic sills was made. The petrography of the crystalline schists and gneisses, was not, however, dealt with in much detail.

Petrographically, the mineralized carbonate rocks differ much from those which are barren. The mineralized carbonate rocks are of two types: 1) The copper bearing dolomites and talc-dolomite rocks, and 2) the lead bearing silicified dolomitic limestones.

Copper ores occur in the dolomites, talc-dolomite rocks and talc schists of Balaldev and Taskhant in Bageshwar. A petrographic study of these rocks revealed the following sequence of events in the alteration of the host rocks and deposition of ores:

1) Dolomitization
2) Formation of Talc
3) Deposition of copper and iron sulphides

The mode of occurrence and nature of the dolomites suggest that they were formed epigenetically. Only the highly dolomitized portions of the country rock hosted the copper ores.

In the lead bearing limestones, the replacement of calcite by dolomite is incomplete and the porphyrotopes of dolomite occur in a fine calcitic matrix. Silicification of these carbonate rocks is a characteristic feature. It is indicated mainly by the replacement of both calcite and dolomite by jasperoid, a cryptocrystalline variety of silica, and also by the presence of quartz in veins and vugs, which are generally surrounded by euhedral dolomites. Occasionally, the quartz crystals in the vugs and veins are associated with some unreplaced calcite and dolomite. Galena is the only sulphide mineral associated with these carbonate rocks and its intimate associate is jasperoid. At times, jasperoid shows automorphic outlines against galena indicating that the latter is younger in age than the former. The lead bearing limestones have the following sequence of events leading to the alteration and mineralization:

1) Incomplete dolomitization
2) Silicification
3) Deposition of lead sulphide

The carbonate rocks which have neither been dolomitised nor silicified, are generally finely crystalline and composed mainly of calcite with a few scattered porphyrotopes of dolomites. They may be called "microsparites".

The petrographic characters of the Bageshwar quartzites indicate that they are mostly orthoquartzites and that their grade of regional metamorphism is low.

The basic sills are mostly altered and epidioritic in composition. Uralite, albite, epidote and other saussurite group of minerals together with some sphene and magnetite are the chief mineral constituents of these sills.

The lithological and petromineralogical characters of the slates, carbonate rocks, quartzites and the basic sills indicate that all were subjected to regional metamorphism of the lowest grade.

5. In the fifth chapter of this work, the author has dealt with the subjects of wall rock alteration, ore zoning and guide to the deposition of copper and lead ores of the area. Ore-microscopic and petrographic studies of the ores and the host rocks respectively, and also the nature and mode of occurrence of mineralized and barren carbonate rocks suggest that at least two successive phases of hydrothermal activity were responsible for the deposition of copper and lead ores in the Shishkhani-Chhanapani-Balaldev belt. The complete absence of any lead ore in the copper deposits and vice versa, is a remarkable feature of these ore deposits. Parageneses of the two phases of hydrothermal alteration of the wall rocks and subsequent mineralization in the carbonate rocks are presented as follows:

		Time
First Phase	Dolomitization	
	Formation of talc	
	Mineralization of pyrite & chalcopyrite	
	Fracturing and brecciation	xxxx
Second Phase	Incomplete dolomitization	
	Silicification	
	Mineralization of galena	

In the first phase of alteration and mineralization, dolomitization was indicated by the appearance of coarse-grained and light-coloured dolomites which were subjected to fracturing and subsequent mineralization by copper and iron sulphides. Some talc was also formed in these dolomites along their fracture and intergranular spaces. The metallic sulphides chiefly occupy voids, fracture spaces and even cleavage partings in the dolomites. Occasionally, both talc and dolomites were being replaced by the ores. Sometimes, blebs and stringers of ore occur in the foliation partings of the talc-schists intercalated with the dolomites.

The second phase of hydrothermal alteration and mineralisation was indicated by the second and incomplete dolomitization of the limestones and their subsequent silicification before the deposition of galena, largely in the silicified portions of the country rock. Frequent replacement of jasperoid by galena in the silicified zones as well their intimate association provide a strong evidence in support of a regular but limited lithologic control on the deposition of the lead sulphide in the incompletely dolomitized limestones. Also, innumerable minor fracture and slip planes, vugs and open spaces in those galena-bearing limestones bear a testimony to the control of at least some minor structures on the localization of lead ore.

Almost all of the deposits of copper and lead in the area show a distinct zonal distribution pattern of their occurrence. There is an inner zone in which dolomite, talc and several copper occurences were encountered. This zone is surrounded by an outer zone consisting largely of dolomitic limestone in which only jasperoid and lead ores occur.

Fourteen limestone samples from the inner zone of copper were chemically analysed to see whether some of their chemical constituents also give any indication of such a zonal distribution around the copper deposits. It is interesting to mention here that the chemical constituents such as Ca/Mg ratio, SiO_2, CO_2 have a zonal distribution since there is a gradual decrease in the value of Ca/Mg ratio with corresponding increase in the CO_2 content, and a decrease in SiO_2 from the barren to the mineralized zones has been recorded.

6. About 50 polished sections of copper and lead ores, collected from the different ancient mining localities in the area were examined in ore-microscope. Mineragraphic studies of these ores revealed the presence of hypogene pyrite and chalcopyrite in the copper and galena, in the lead deposits. The rest of the identified ore minerals are supergene. The following minerals were identified in the copper ores:- Hypogene: Pyrite and chalcopyrite. Supergene: Covellite, chalcocite, cuprite, malachite, azurite and limonite. Lead ores have the following assemblage of minerals:- Hypogene: galena. Supergene: Anglesite.

The primary textural relation between pyrite and chalcopyrite has largely been obliterated due to the formation of supergene chalcocite at the contact of the above two hypogene minerals. Sometimes, however, pyrite shows automorphic outlines against chalcopyrite. There are also some veins of chalcopyrite in pyrite which is partially replaced by supergene chalcocite displaying 'relict' and sometimes 'reticulated vein' textures. Chalcopyrite without any exception is rimmed and partly replaced by covellite which, in turn, is rimmed and replaced by chalcocite of a second generation. The chalcopyrite areas generally display a 'mesh pattern'. Chalcocite is again replaced by cuprite, and malachite often fills the vugs which are surrounded by cuprite. Malachite also replaces both cuprite and chalcocite. Both azurite and limonite occur as vein minerals in malachite. The paragenetic sequence of the ore minerals and the associated gangues in the Bageshwar copper-lead deposits has been worked out as a result of ore-microscopic and thin section studies. (Table VIII).

7. Studies on the following lines provided valuable evidence in support of the hydrothermal origin (epithermal type) of the copper and lead ores of Bageshwar:

a) Ground preparation
b) Wall rock alteration
c) Zoning in copper-lead deposits. Zonal distribution of Ca/Mg ratio, CO_2 and SiO_2 contents in the carbonate rocks around the copper deposits.
d) Temperature of mineral formation.
e) Gangue minerals associated with the deposits.
f) Paragenesis and the phases of mineralization.
g) Structural control on ore localization.

Based on a study of the nature of wall rock alteration, mineralogy, and nature and mode of occurrence of the hypogene sulphide ores which were related to two successive phases of mineralization, the copper-lead deposits of Bageshwar have been classified as 'epithermal type'.

The source of hydrothermal solutions, however, continues to be enigmatic. In the present state of our knowledge of the Himalayan metallogeny which is still in the realm of speculation nothing more can be said than associating vaguely the tertiary granites, which intruded into the deeper parts of the older Central Himalayan gneisses and granites, as the possible source of these copper and lead bearing hydrothermal solutions.

EXPLANATION OF PLATES

PLATE - I

Fig. 1 Effect of differential weathering on a cherty limestone.

Fig. 2 Rhombohedral joint pattern in limestones. Locality - North of Baligad.

Fig. 3 Current ripple marks on quartzites near Shishkhani village; Bageshwar.

Fig. 4 Stromatolites - concavo-convex laminae of collenia; Locality - 1 mile south of Bageshwar.

PLATE - II

Fig. 1 Elephant skin weathering of limestones. Locality - Tunera.

Fig. 2 Folded slates near Dafat Gad - Sarju river confluence.

Fig. 3 Fault breccia near Tamkhani.

PLATE - III

Fig. 1 An outcrop of well jointed quartzite near Bageshwar.

Fig. 2 Quartz vein in Baijnath crystallines near Kathathbara.

Fig. 3 Current bedding in quartzites - Gomati river bridge outcrops, Bageshwar.

PLATE - IV

Fig. 1 Minor plunging folds in the calcareous phyllites near Anarsa.

Fig. 2 An outcrop of fault breccia near Tunera. Note the fragments of slate in a calcareous matrix.

Fig. 3 Minor plunging folds in slates near Belauna Sera.

Fig. 4 Fault scarp in calcareous phyllites two furlongs south of Belauna Sera.

PLATE - V

Fig. 1 Northwesterly plunging slate - limestone contact near Kaligad.

Fig. 2 Minor folds in the Baijnath crystallines near Mandal Sera.

Fig. 3 A composite fault scarp near Tunera.

PLATE - VI

Fig. 1 The intersection of three divergent trends in Mandal Sera region is marked by an alluvial plain covering an extent of about 2.5 sq. miles.

Fig. 2 A plunging minor anticline in calcareous phyllites near Chhana.

PLATE - VII

Fig. 1 Idiotopic porphyrotopes of dolomite (light coloured) set in a xenotopic fine calcitic matrix. x 36

Fig. 2 Coarse dolomite developing from fine calcite. x 36

Fig. 3 Replacement of calcite (grey) by jasperoid (white). Note the rugged and irregular contact. x 36

Fig. 4 Replacement of calcite (grey) by jasperoid. Note the unreplaced relicts of the host in the guest mineral. x 36

PLATE - VIII

Fig. 1 Dolomite in contact with calcite tends to be euhedral. Also note the development of void which has been later filled by quartz. x 36

Fig. 2 Note the euhedral rhombic dolomite developing from anhedral fine calcite. Crossed nicols. x 36

Fig. 3 Dolomite being replaced by jasperoid. Note also relict texture. x 36

Fig. 4 Jasperoid filling vug and replacing carbonates. x 100

PLATE -IX

Fig. 1 A vug lined by euhedral dolomite grains, is filled and replaced by jasperoid. Note an unreplaced grain of carbonate in the jasperoid. x 36

Fig. 2 The same field as in Fig. 1 under crossed nicols. x 36

Fig. 3 The intimate association of jasperoid (white) and galena (black). Also note some subrounded grains of jasperoid within the galena. Dark grey is relict of calcite. Thin section. x 36

Fig. 4 Galena-jasperoid relation. Note the automorphic tendency of jasperoid against galena. Thin section x 36

PLATE - X

Fig. 1 Galena-jasperoid association. Note the penetration of galena into jasperoid and also the convexity of jasperoid towards galena. Thin section. x 100

Fig. 2 Replacement of both calcite (dark grey) and dolomite (light grey) by jasperoid (white). x 36

Fig. 3 Well developed rhombohedral cleavage in dolomite. x 36

Fig. 4 Opaque minerals (pyrite-chalcopyrite) occupy the intergranular space in dolomite and also the fractures. Thin section. x 36

Plate - XI

Fig. 1 Porphyrotopic texture of dolomitic limestones adjacent to the mineralized zones. x 36

Fig. 2 The porphyrotopes are larger in size and greater in number in the transitional zones adjacent to the mineralized zones. Thin sections. Crossed Nicols. x 36

Fig. 3 General texture of calcareous phyllite. x 36

Fig. 4 Cross fibres of calcite in the calcareous phyllite. x 36

PLATE - XII

Fig. 1 General texture of barren micritic limestone. x 36

Fig. 2 General texture of barren 'microsparites'. Crossed Nicols. x 64

Fig. 3 General texture of quartzites. Note the porphyroblasts of quartz in a matrix of fine chert and opaque dust. Crossed Nicols. x 36

Fig. 4 Rounded or subrounded grains of quartz in the quartzite. Crossed Nicols. x 36

PLATE - XIII

Fig. 1 The effect of metamorphism on the orthoquartzite is also indicated by the presence of quartz grains preferredly oriented. Also note wavy extinction in some quartz grains. Crossed Nicols. x 36

Fig. 2 Mosaic texture developed in quartzites. Crossed Nicols. x 36

Fig. 3 General texture of graphitic quartz schist. x 36

Fig. 4 Fibrous (actinolitic) hornblende, uralite in the altered basic sills. x 165

PLATE - XIV

Fig. 1 Intimate association of fresh albite and the saussurite in the altered basic sills. Crossed Nicols. x 100

Fig. 2 Sphene with a core of magnetite in the altered basic sills. x 165

Fig. 3 Augen structure in the crystalline gneiss. x 36

Fig. 4 Muscovite-quartzite from crystalline schist. Crossed Nicols. x 165

PLATE - XV

Fig. 1 Extremely coarsely crystalline dolomite with clusters of copper sulphides.

Fig. 2 Loosely compacted dolomite grains with fractures. Thin section. x 36

Fig. 3 Highly fractured dolomite-talc rock from completely dolomitized zones. Thin section. x 36

Fig. 4 Jasperoid replacing both calcite and dolomite. Note the relict texture and also the rugged contact calcite (dark grey) jasperoid (white) and dolomite (light grey) x 36

PLATE - XVI

Fig. 1 Microvug lined by dolomite is filled with jasperoid. Also note the relicts of carbonates in jasperoid.

Fig. 2 Note the textural variation of the jasperoid which partially replaced the carbonates and the quartz which filled up open spaces. x 36

Fig. 3 Same field as in Fig. 2. Crossed Nicols. x 36

Fig. 4 Pyrite-chalcopyrite relation. Note the euhedral tendency of original pyrite. Pyrite has been partially replaced by chalcocite (oil immersion). Polished section. x 64

PLATE - XVII

Fig. 1 A vein of chalcopyrite in pyrite. Also note the replacement of pyrite by chalcocite at the contact of pyrite and chalcopyrite. Chalcopyrite is being oxidized by some black copper oxide (?). x 64 Oil immersion.

Fig. 2 Chalcocite replacing pyrite along irregular fractures. x 40

Fig. 3 Chalcocite replacing pyrite. Note the irregular contacts of the two minerals. x 64 Oil immersion.

Fig. 4 Unreplaced relicts of pyrite in chalcocite areas; displaying 'ice cake' texture. x 36

PLATE - XVIII

Fig. 1 Rim replacement of chalcopyrite by covellite. Covellite in turn has been rimmed and replaced by chalcocite. x 475.

Fig. 2 Reticulated vein texture or mesh pattern in chalcopyrite areas. x 40

Fig. 3 Chalcocite replacing pyrite pseudomorphically. x 36

PLATE - XIX

Fig. 1 Malachite filling vug lined by cuprite. x 64. Oil immersion. Polished section.

Fig. 2 Malachite replacing chalcocite. x 40. Polished section.

Fig. 3 Malachite being veined by limonite. x 64. Oil immersion. Polished section.

Fig. 4 Galena filling vein and grain boundaries of loosely compacted dolomite grains. x 40 Polished section.

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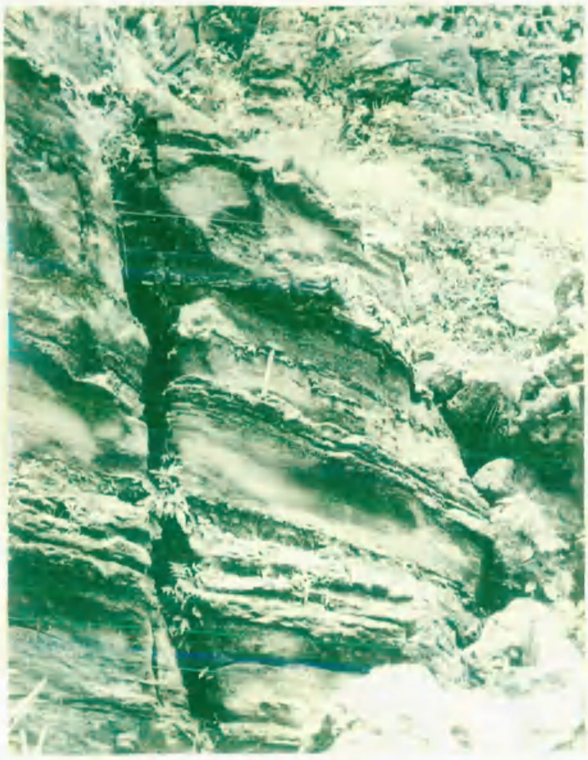
Plate I



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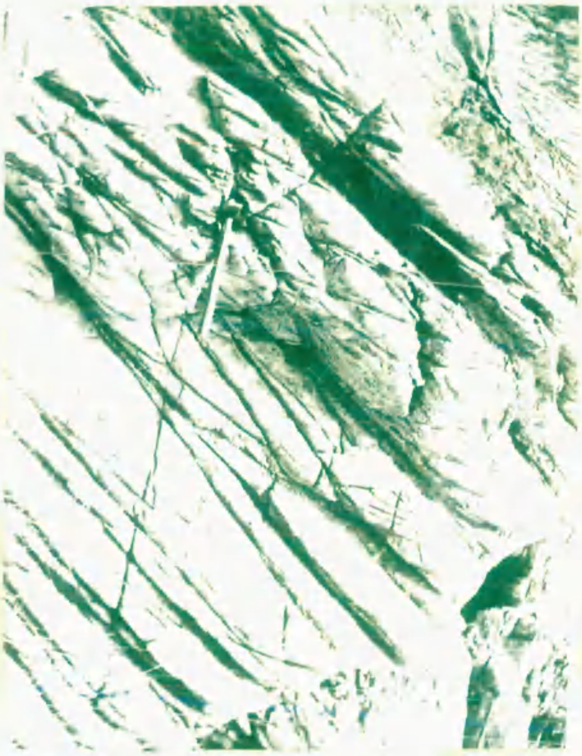
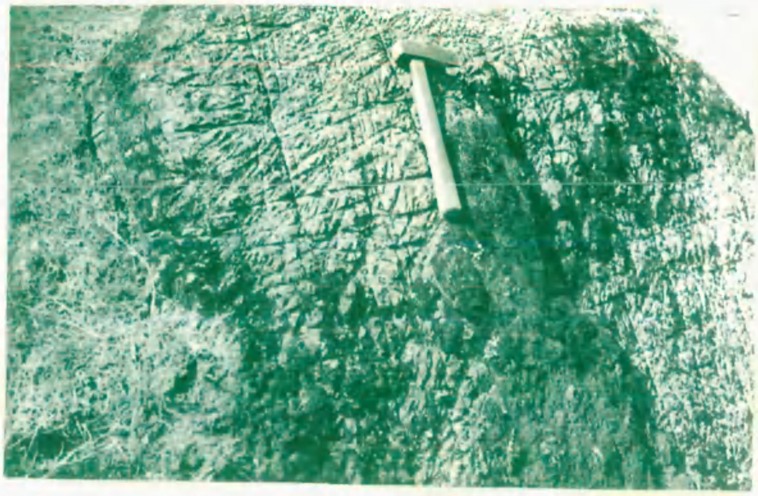


FIG. 2.

FIG. 3.

FIG. 4.

Plate 11



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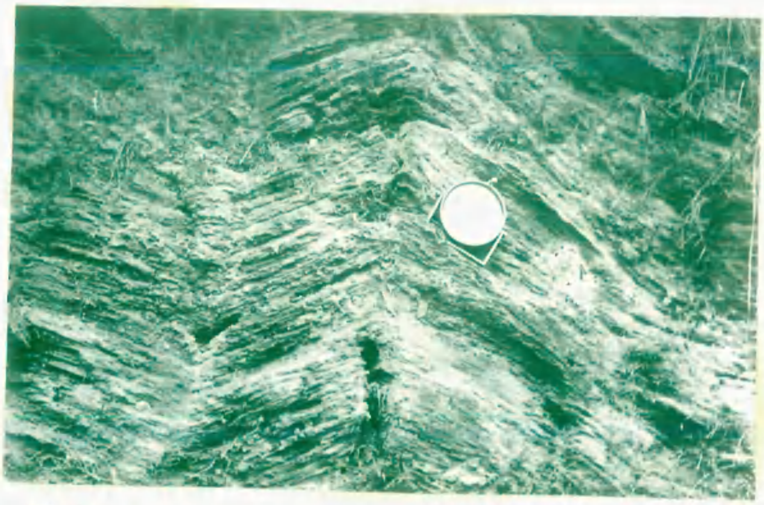

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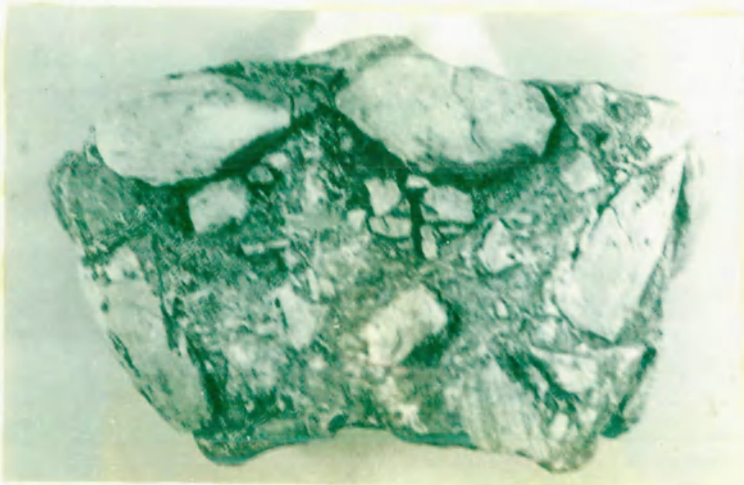
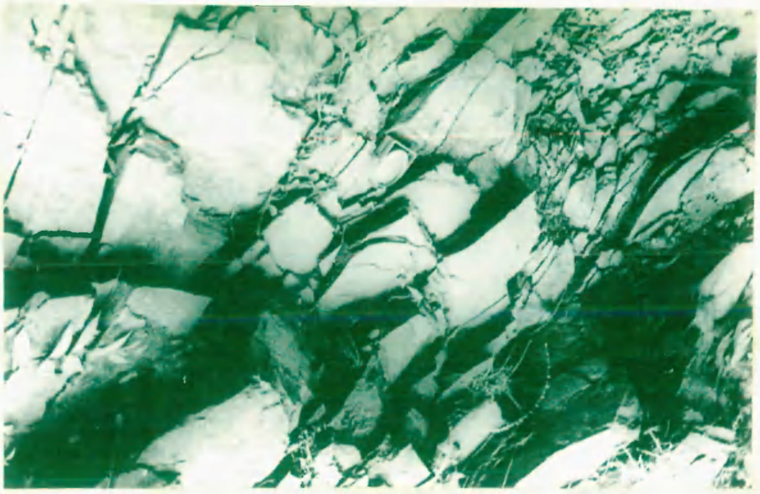


FIG. 3.

Plate III



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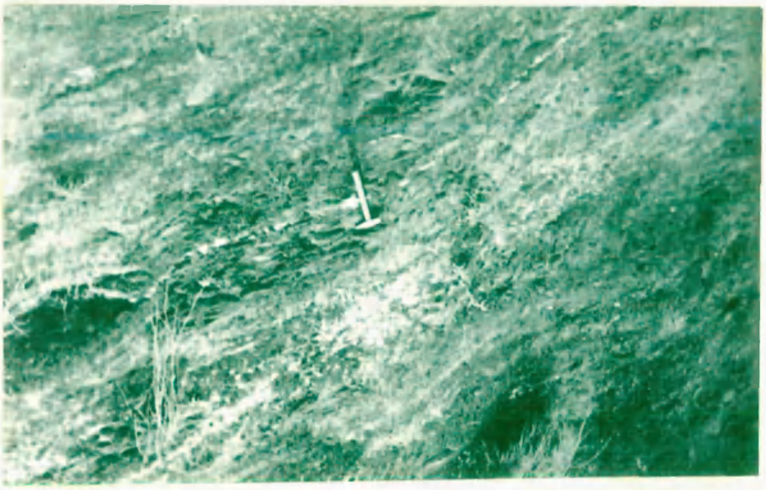

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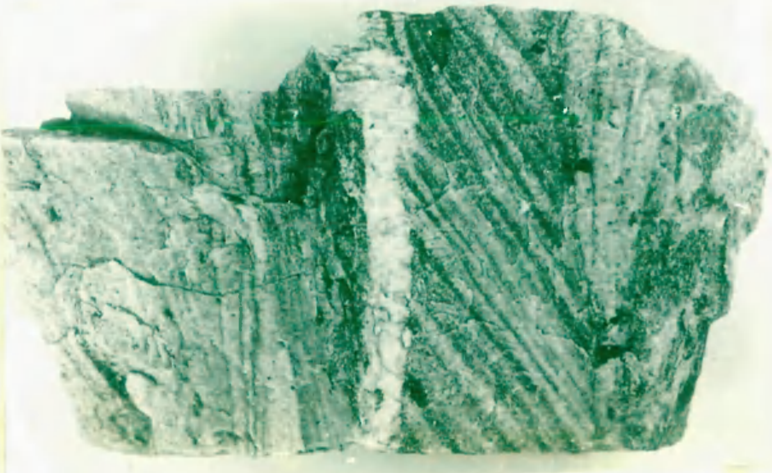
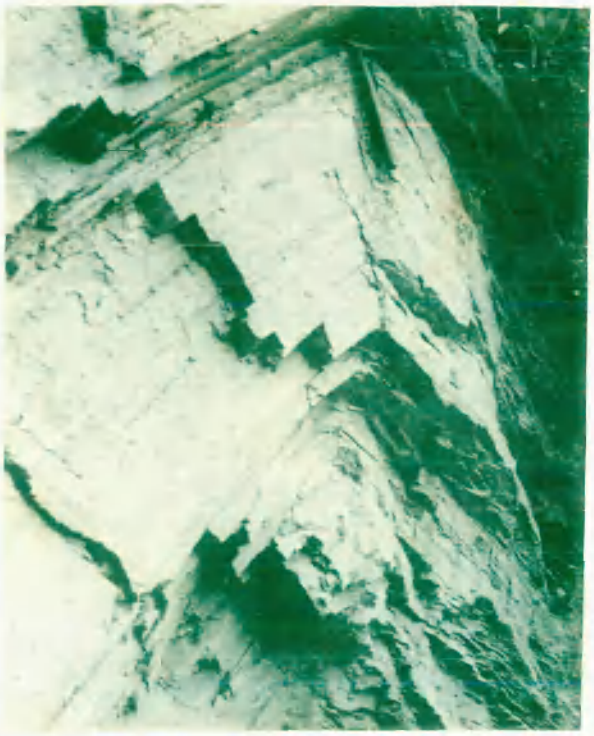


FIG. 3

Plate IV



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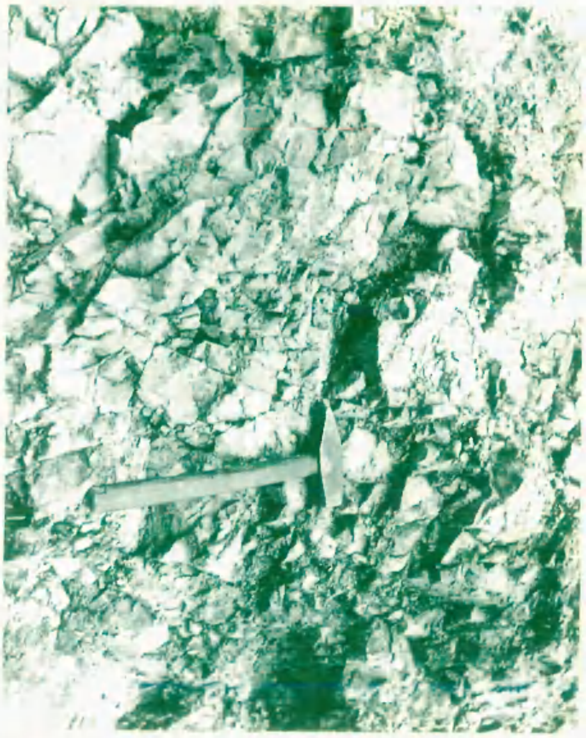


FIG. 2.

FIG. 3

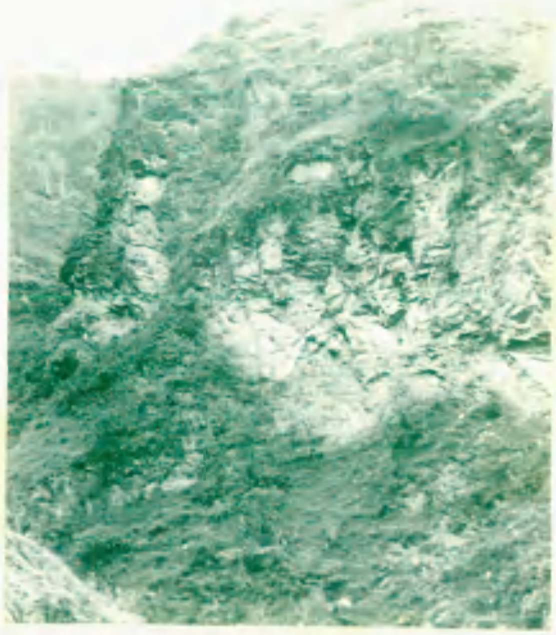


FIG. 4

Plate V

FIG. 1.

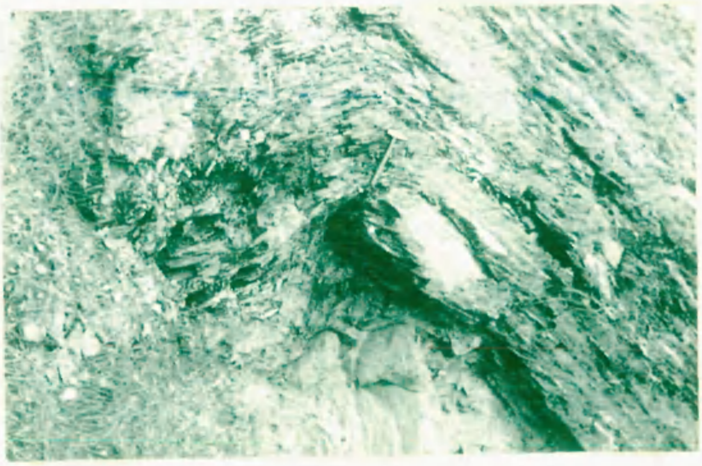


FIG. 2

FIG. 3

Plate VI

FIG. 1.

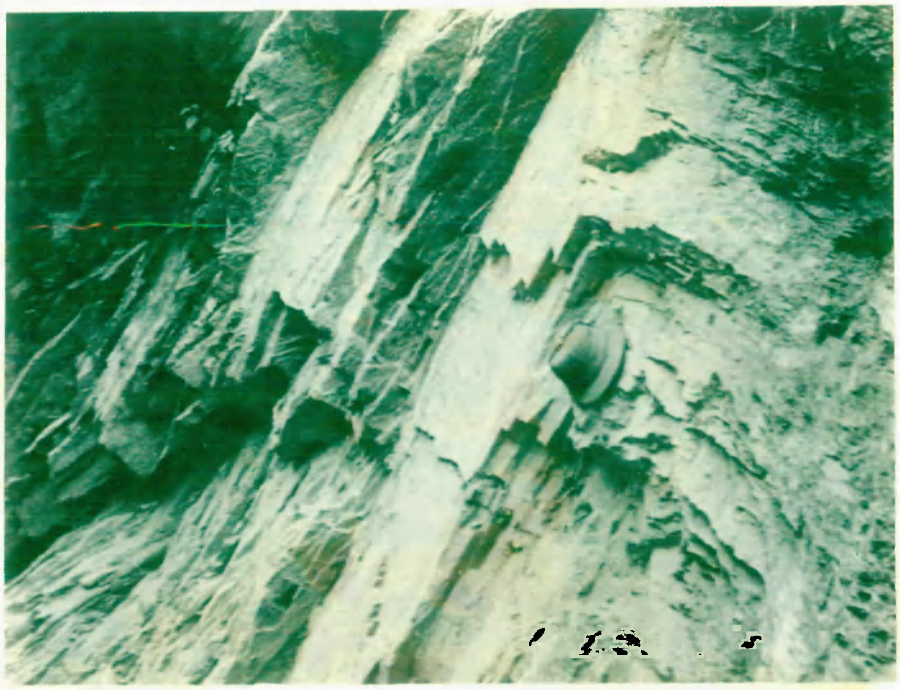


FIG. 2

Plate VIII

FIG. 1.

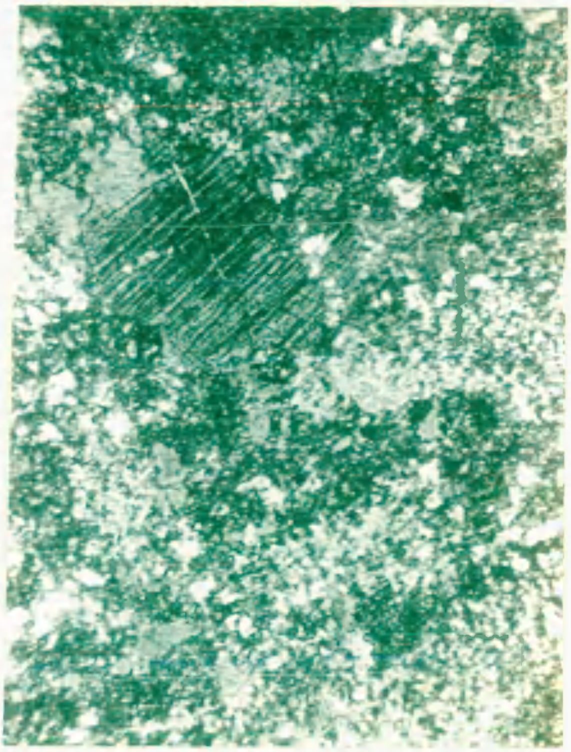


FIG. 2.

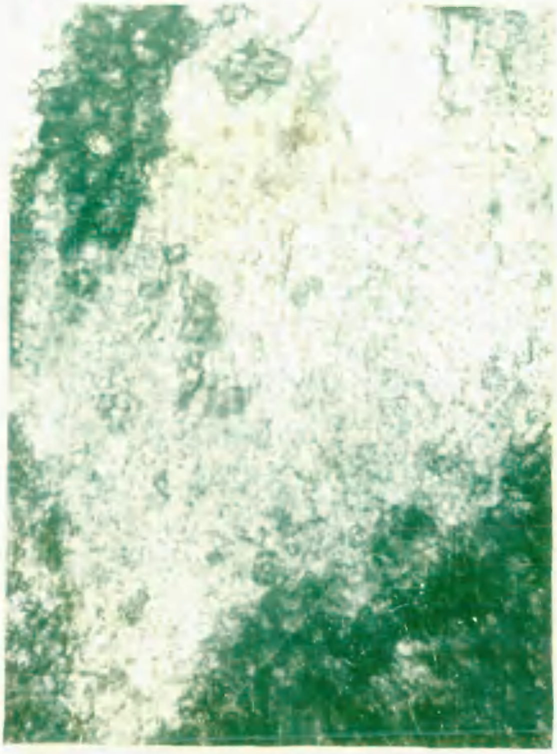


FIG. 3.

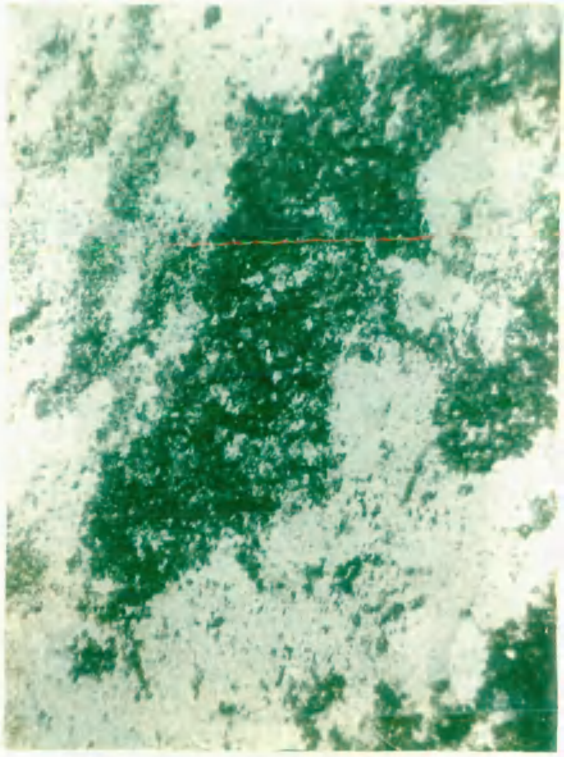


FIG. 4.

Plate VIII

FIG. 1

FIG. 2.

FIG. 3.

FIG. 4.

Plate IX

FIG. 1.

FIG. 2.

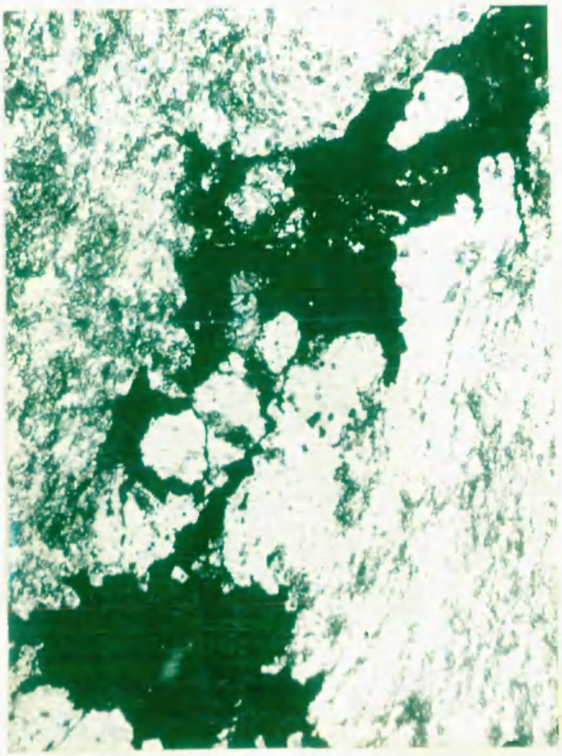


FIG. 3.

FIG. 4.

Plate X

FIG. 1.

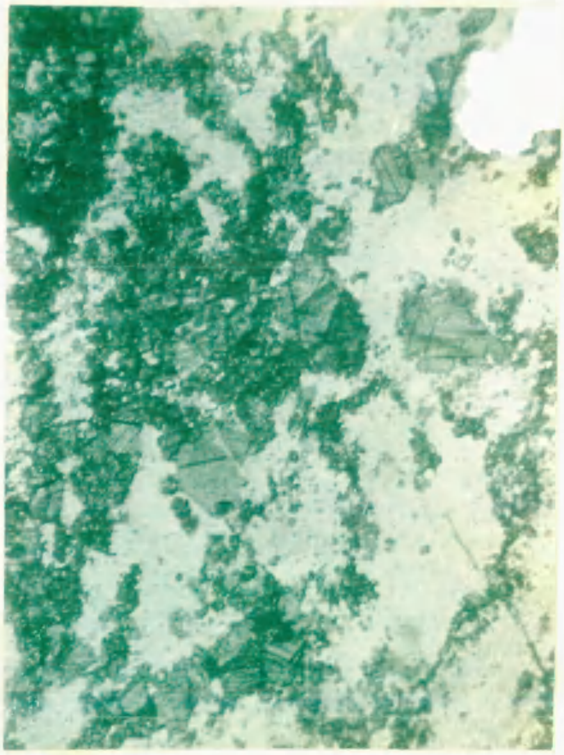


FIG. 2.

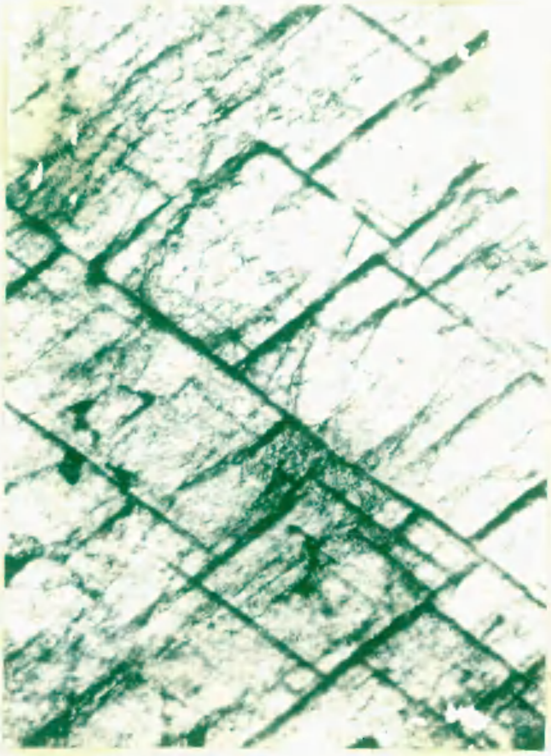


FIG. 3.

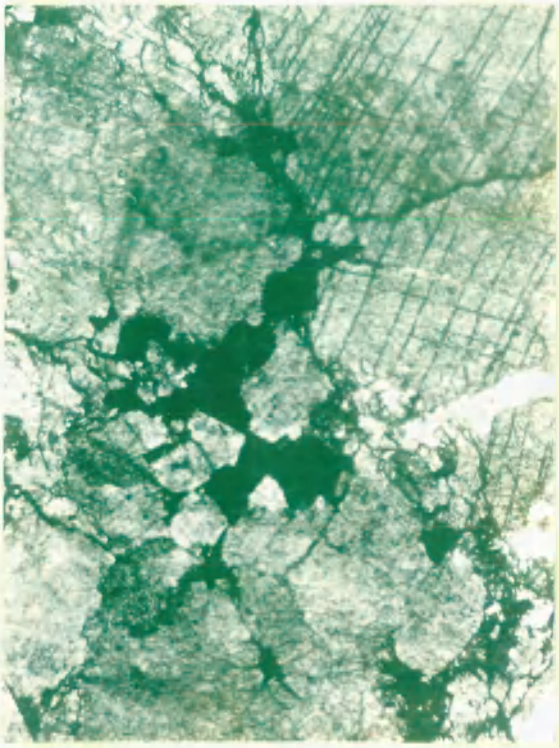
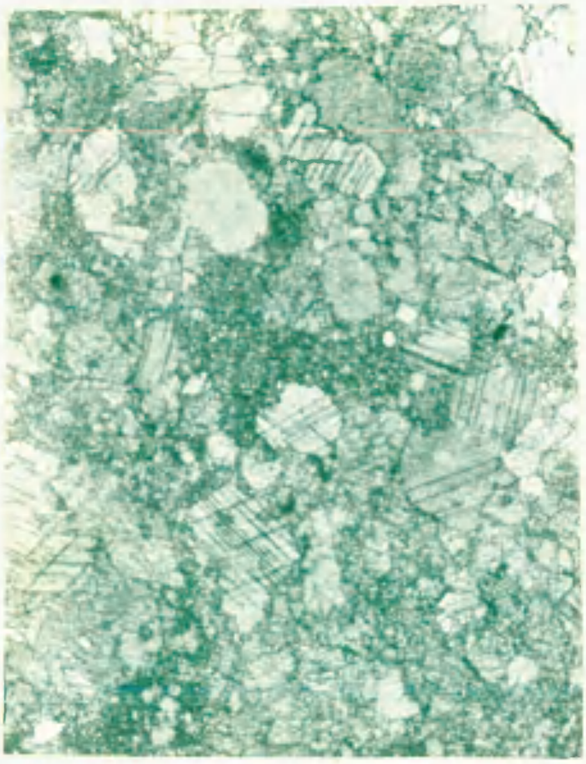


FIG. 4.

Plate XI



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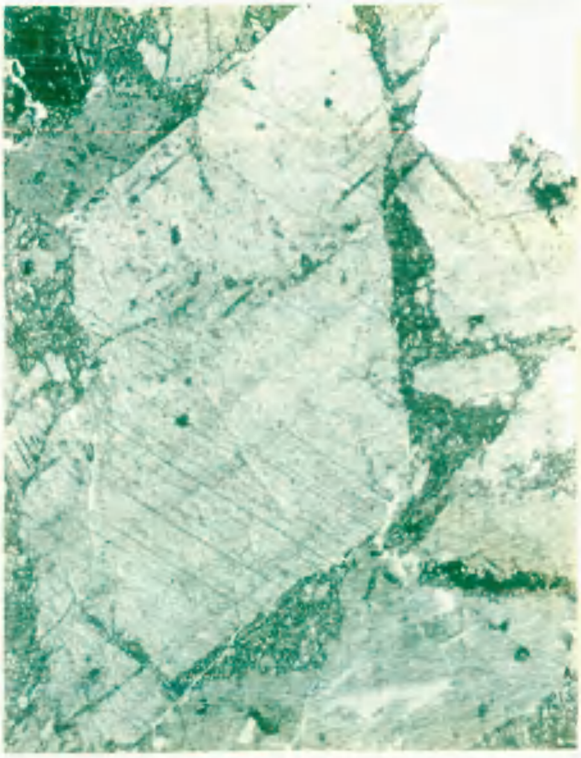


FIG. 2.

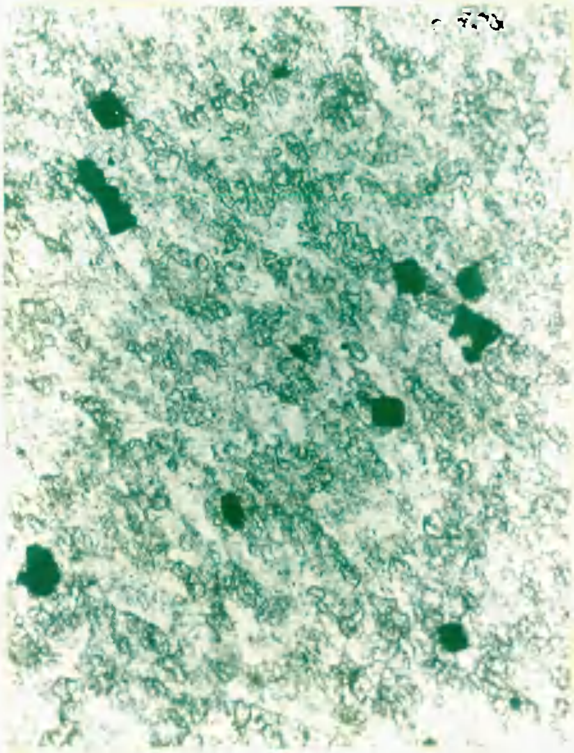
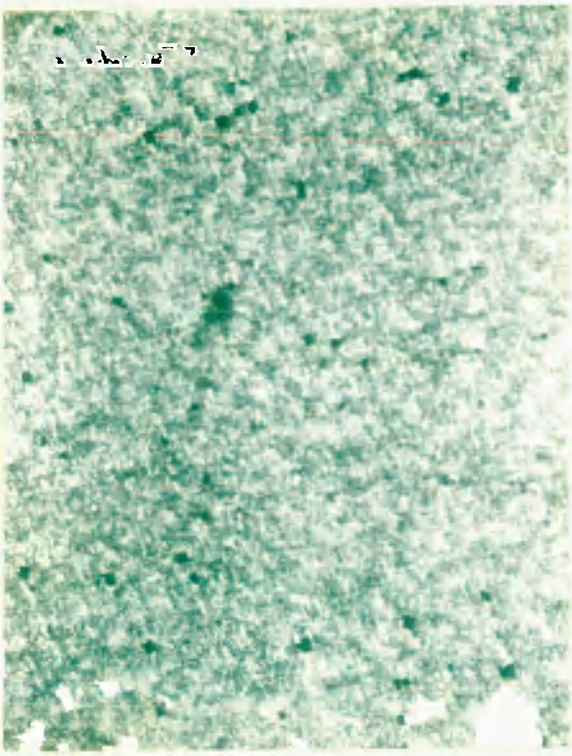


FIG. 3.

FIG. 4.

Plate XII



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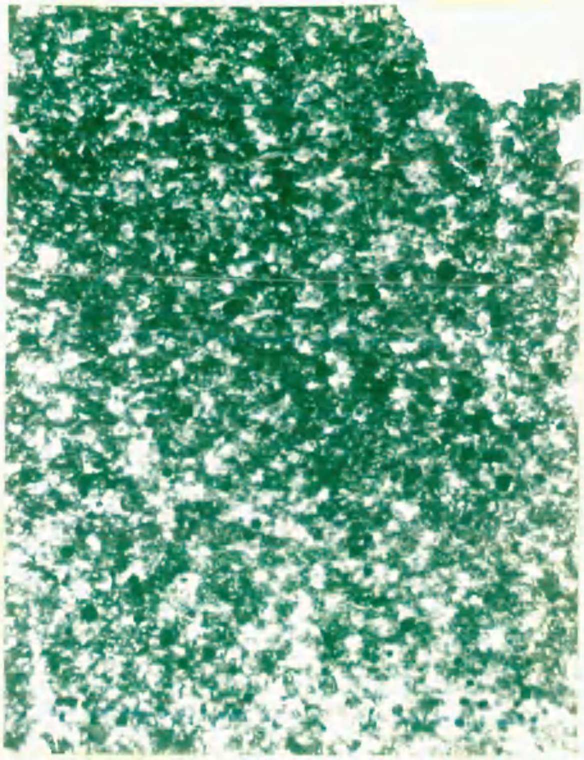
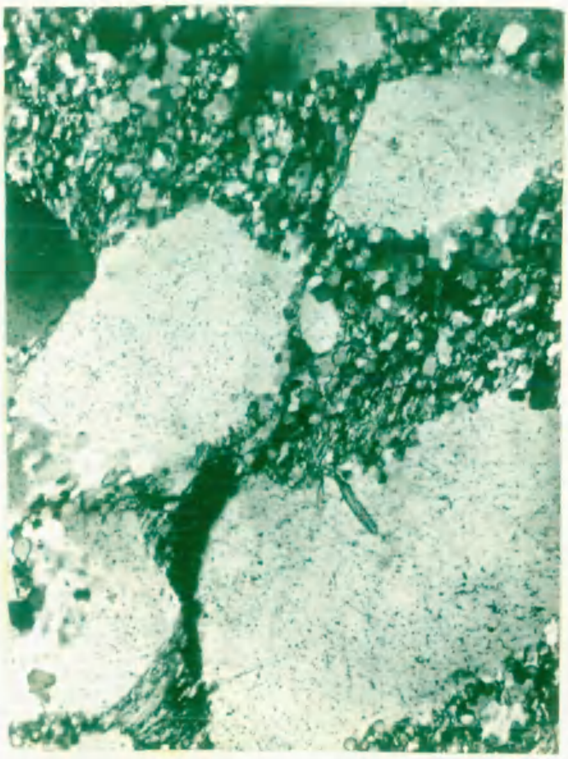


FIG. 2



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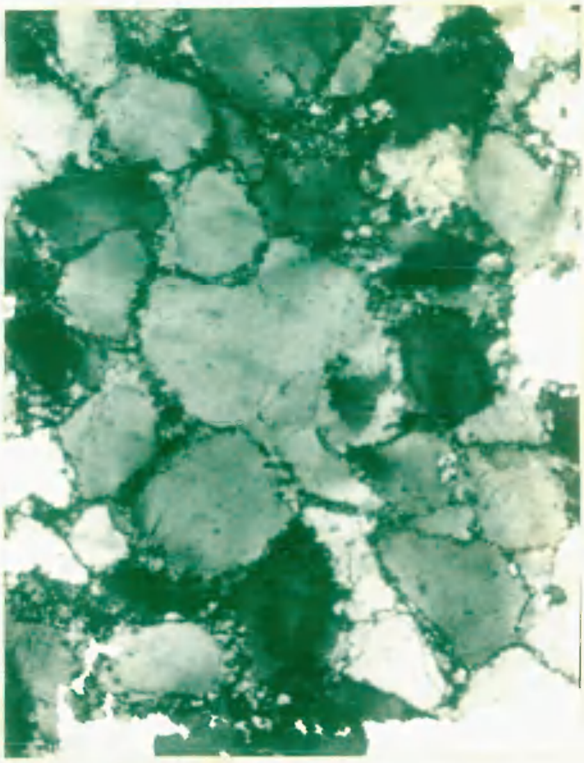


FIG. 4.

Plate XIII

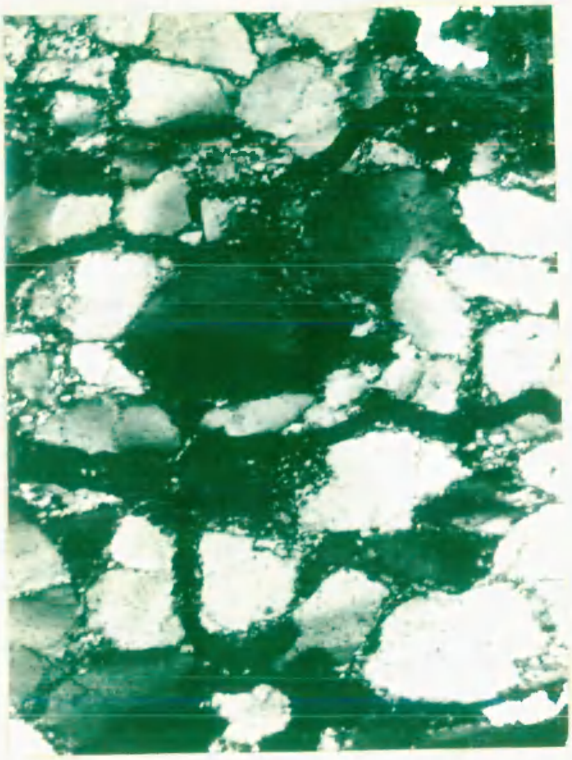


FIG. 1.

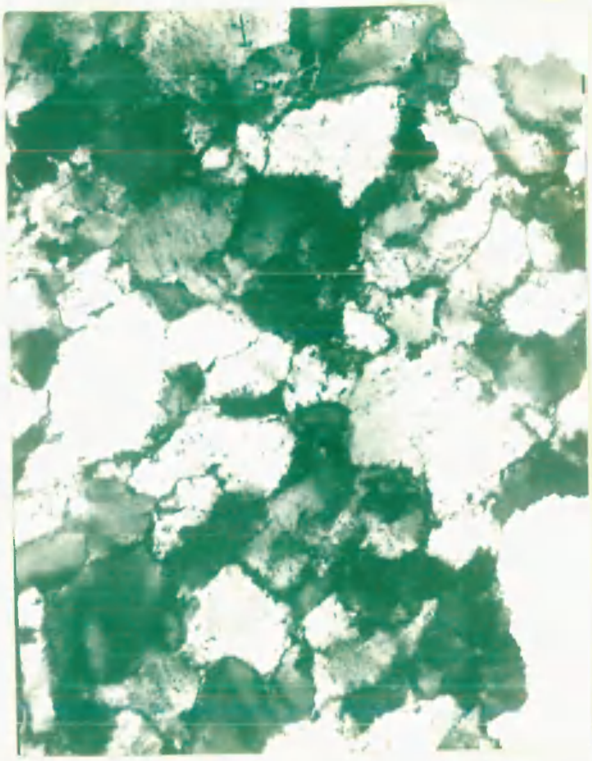


FIG. 2.

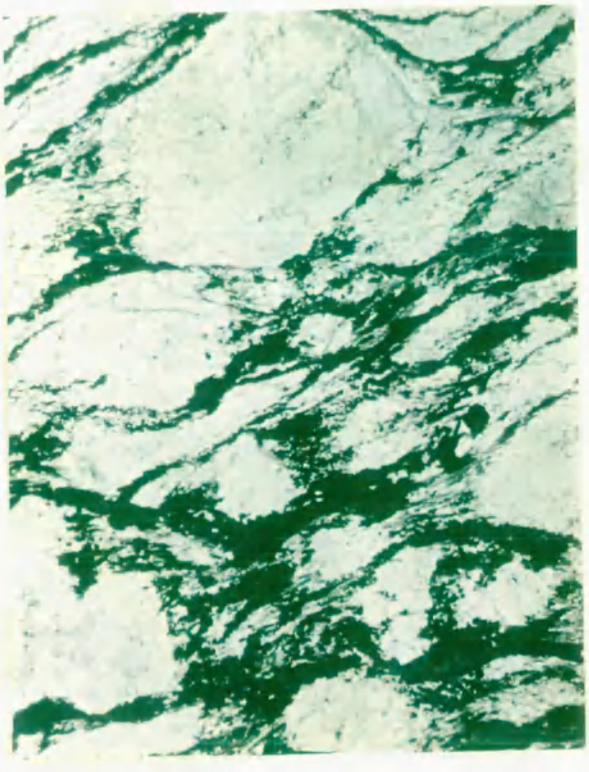


FIG. 3.

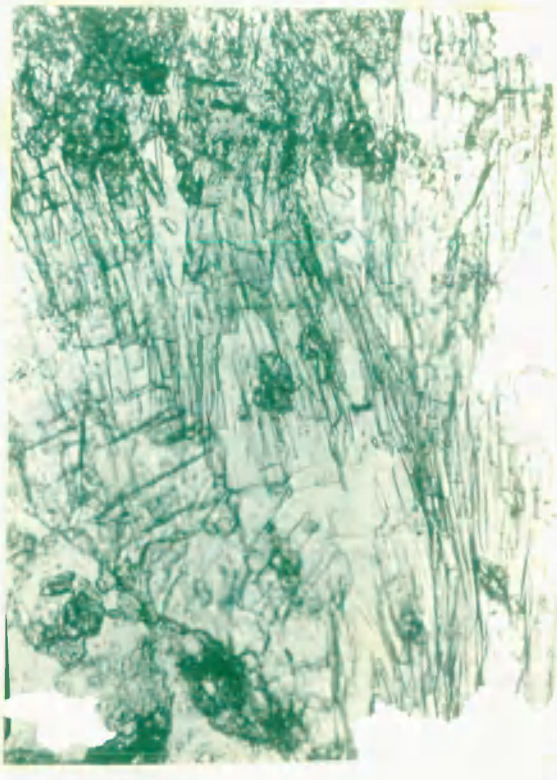


FIG. 4.

Plate XIV

FIG. 1.

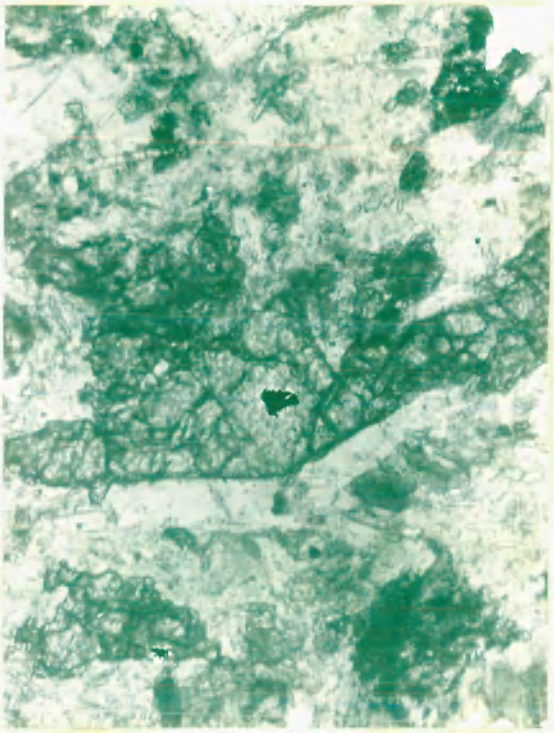


FIG. 2.

FIG. 3.

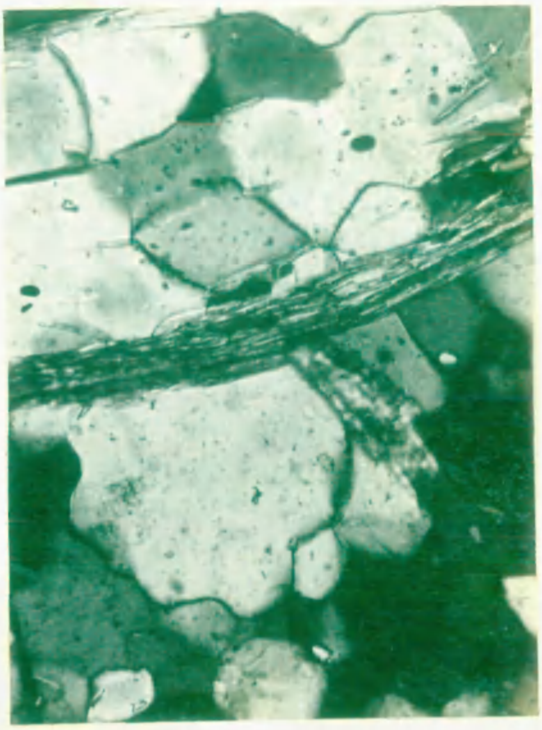


FIG. 4.

Plate XV

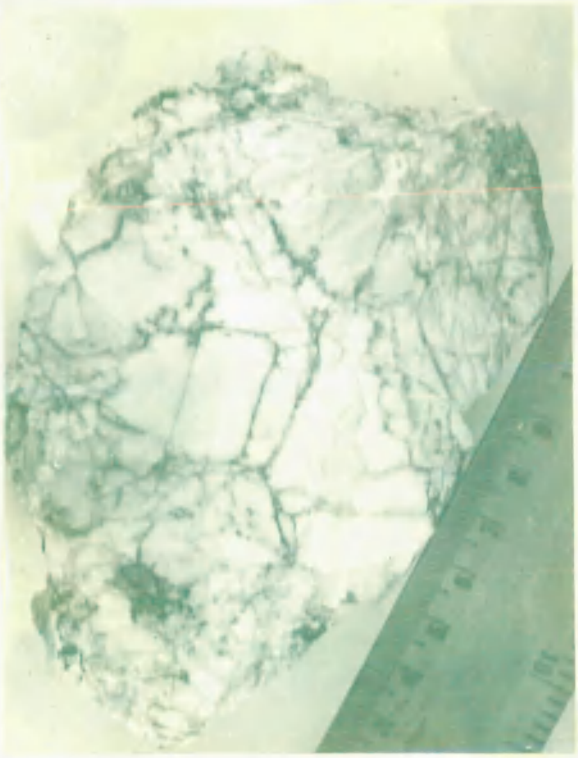


FIG. 1.

FIG. 3.

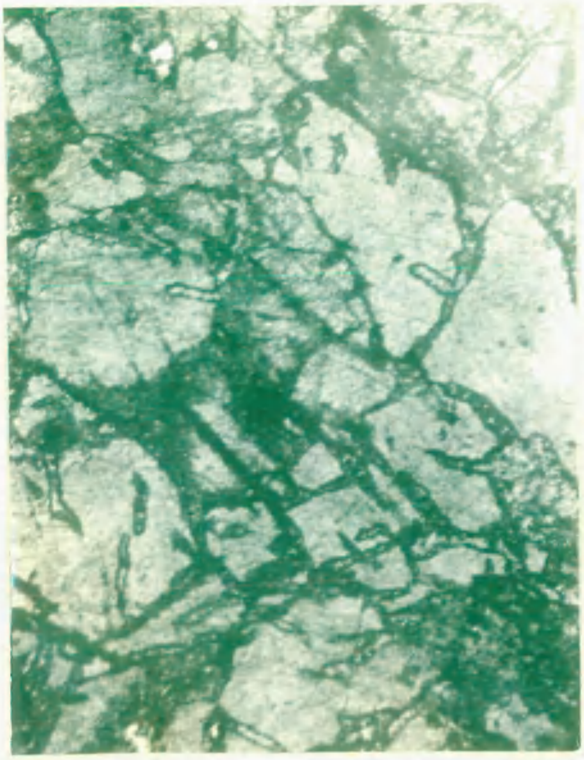


FIG. 2.

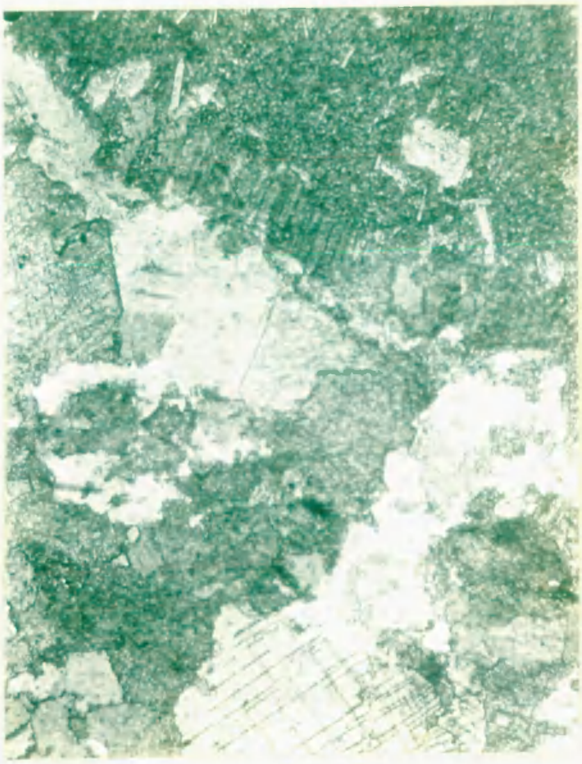
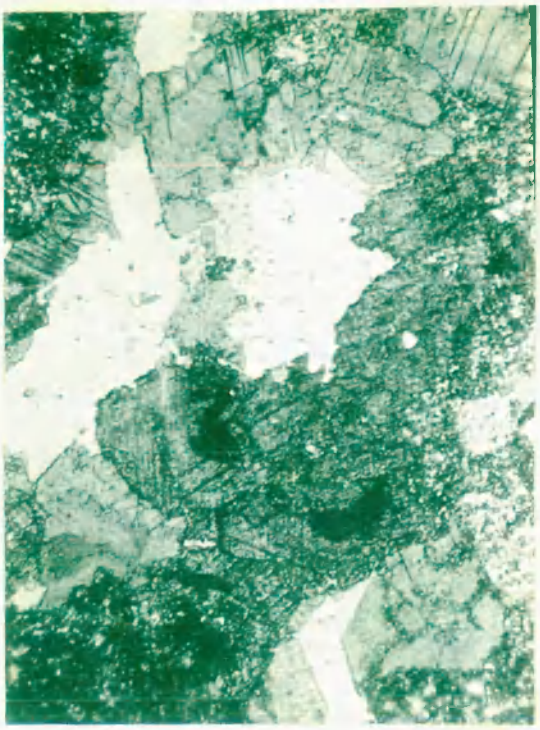


FIG. 4.

Plate XVI



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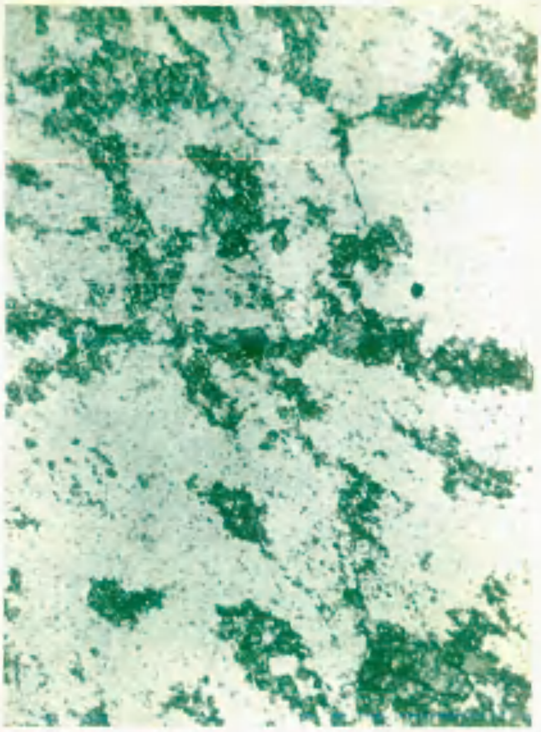


FIG. 2.

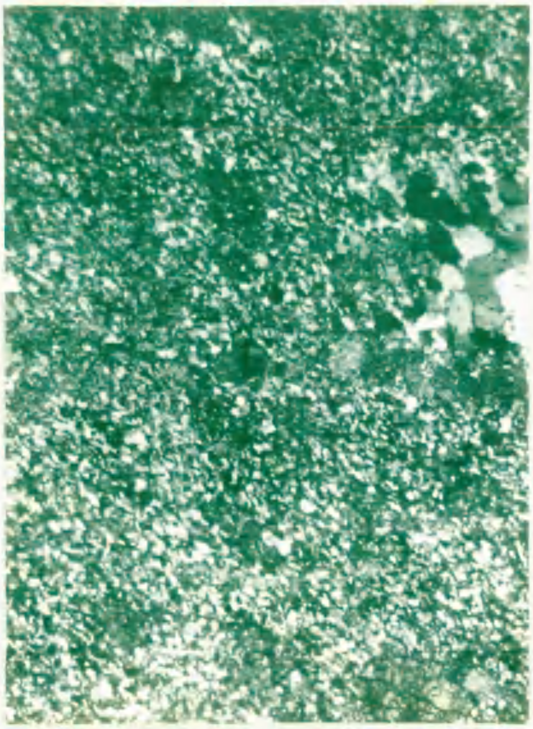


FIG. 3.

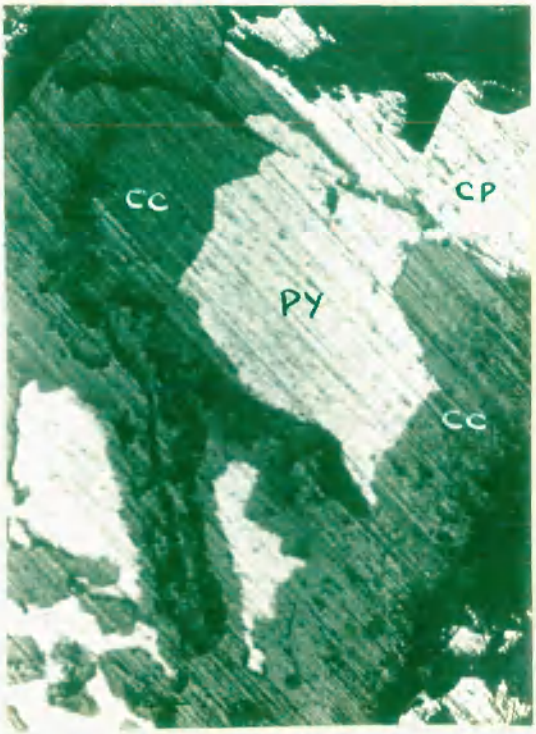
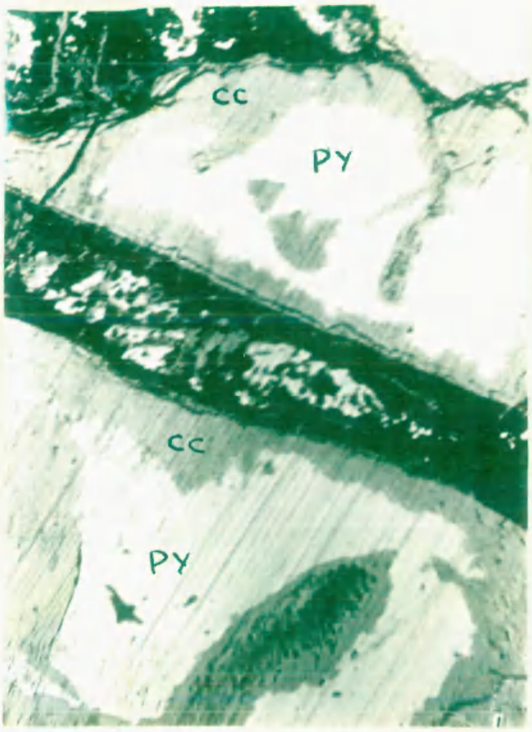


FIG. 4.

Plate XVII



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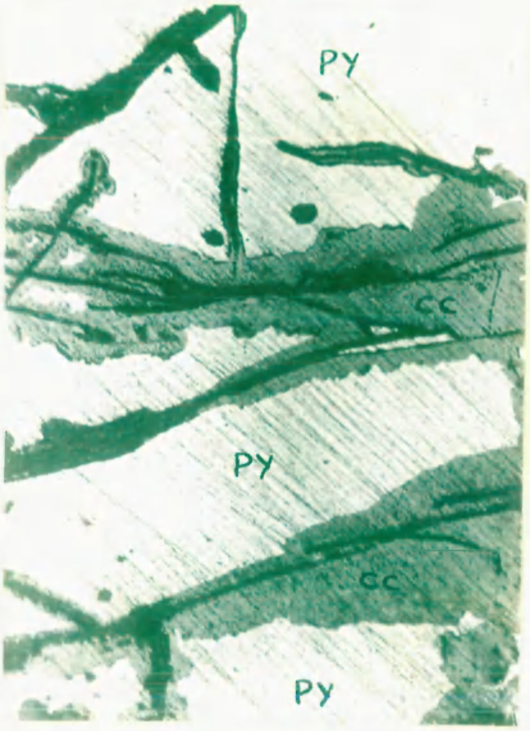

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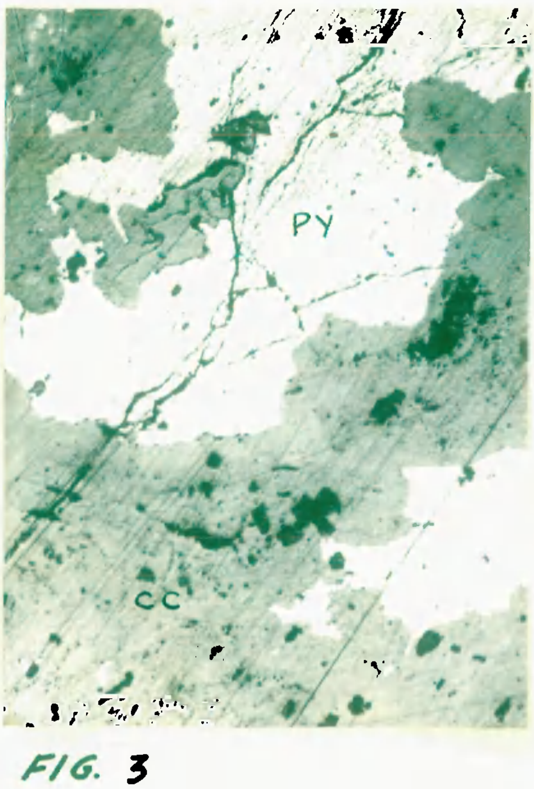

FIG. 3

FIG. 4.

Plate XVIII

FIG. 1.

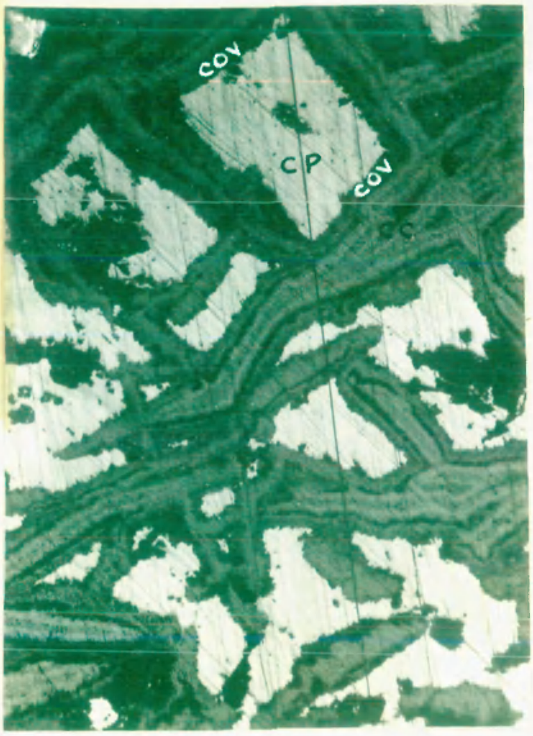

FIG. 2.

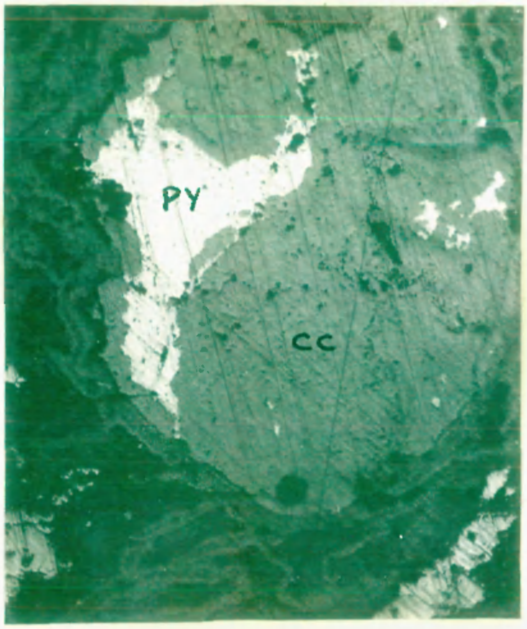

FIG. 3.

Plate XIX

FIG. 1.

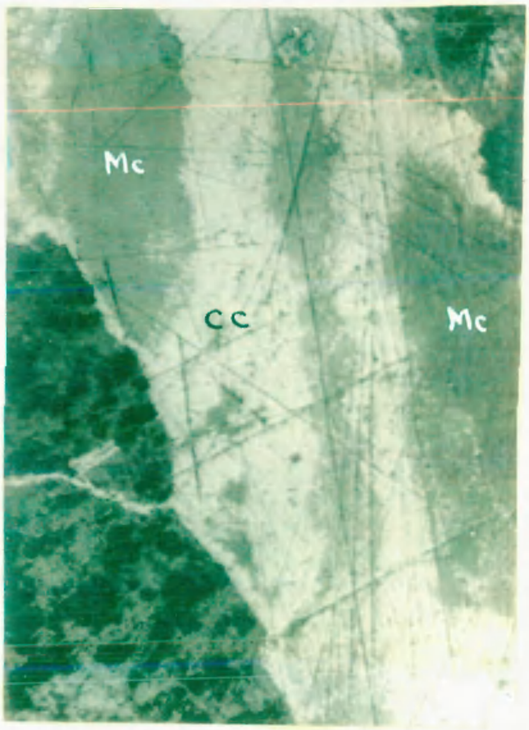

FIG. 2.

FIG. 3

FIG. 4.